MISCELLANEOUS PAPER H-68-5

BOUNDARY EFFECTS OF UNIFORM SIZE ROUGHNESS ELEMENTS IN TWO-DIMENSIONAL FLOW IN OPEN CHANNELS

by

B. J. Brown

Y. H. Chu

December 1968

Sponsored by

Assistant Secretary of the Army (R&D)
Department of the Army

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

72

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D	
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)	
1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP
3. REPORT TITLE BOUNDARY EFFECTS OF UNIFORM SIZE ROUGHNESS ELEMENTS IN TWO-DIMENSIONAL FLOW IN OPEN CHANNELS	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report	
5. AUTHOR(S) (First name, middle initial, last name) Bobby J. Brown, Yen H. Chu	
6. REPORT DATE December 1968	7a. TOTAL NO. OF PAGES 67 / 7b. NO. OF REFS 17
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) Miscellaneous Paper H-68-5
b. PROJECT NO. 1L013001A91A Item L	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Assistant Secretary of the Army (R&D) Department of the Army

13. ABSTRACT

Tests were conducted to investigate the characteristics of the vertical velocity distribution in flow in wide channels with large relative roughness. The study was basically a two-dimensional investigation of the boundary roughness effects in turbulent flow. The investigation was conducted in a 48-ft-long, 2-1/2-ft-wide flume with 1/8-, 1/2-, 3/4-, and 1-in. crushed limestone and 3/4-in. concrete cubes as the boundary roughness. Results indicate that the root-mean-square value σ of the boundary roughness heights is related to the Nikuradse equivalent sand grain roughness k_s and that the root-mean-square value can be treated as a roughness parameter for boundaries of densely spaced, irregular, randomly placed roughness elements of uniform size. Appendix A includes the experimental data. Appendix B describes the special instrumentation used for measuring the vertical velocity profiles within the flow.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Boundary layer flow						
Channel flow						
Open-channel flow						
Roughness						
Two-dimensional flow						

Unclassified

Security Classification

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ARMY-MRC VICKSBURG, MISS.

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FOREWORD

This study was funded by Department of the Army Project 1L013001A91A, "In-House Laboratory Independent Research Program," Item L, sponsored by the Assistant Secretary of the Army (R&D). It was conducted during the period July 1964 to July 1968 at the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, under the direction of Mr. E. P. Fortson, Jr., Chief, Hydraulics Division. The study was assigned to the Analysis Section of the Hydraulic Analysis Branch. Messrs. F. B. Campbell and E. B. Pickett were, successively, Chiefs of the Hydraulic Analysis Branch, and Mr. R. G. Cox was Chief of the Analysis Section during the study.

The initial phase of the study, 28 July 1964 to 3 September 1965, was accomplished by SP 4 J. S. Watkins under the technical supervision of Mr. Pickett. During this period the test facility building was constructed, the test equipment was designed, fabricated, and installed, and an extensive literature search was completed. SP Watkins' duty tour ended in September 1965.

The project was generally inactive during the period September to December 1965, at which time Mr. B. J. Brown was assigned as project engineer under the technical supervision of Mr. Cox. During the period 6 December 1965 to 20 April 1966, the test facility and equipment were checked out and the first experimental data were obtained. A First Interim Report dated April 1966 was prepared by Mr. Brown and describes the test procedures used and test data and results obtained with two types of flume invert roughness. Mr. Brown left for military duty in mid-April 1966.

Second and Third Interim Reports were prepared by Mr. Y. H. Chu,

Hydraulic Research Engineer, and SP 5 J. Canton during the period September 1966 to October 1967.

Mr. Brown (CPT, USAR) was assigned to the project in a military capacity during the period 1 February to 21 April 1968 and subsequently reassigned as civilian project engineer on 22 April 1968 upon completing his tour of active duty.

This, the final report on the study, summarizes all the test data and results to date. The report was prepared by Messrs. Brown and Chu. The basic data were obtained and analyzed by SP Canton during the period September 1966 through January 1968.

Directors of the Waterways Experiment Station during the conduct of the investigation and the preparation and publication of this report were COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE. Technical Director was Mr. J. B. Tiffany.

CONTENTS

NOTATION

a,b,c	axial radii of the stone
C	Chezy's resistance coefficient
d	corrected flow depth, ft
D_{50}	mean stone diameter, ft
f	Darcy-Weisbach friction factor
g	gravitational acceleration, ft/sec^2
h	vertical distance measured from top of roughness, ft
k	effective roughness height, ft; $k = 2\sigma$
k_s	Nikuradse's equivalent sand grain roughness, ft
n	Manning's roughness coefficient
N	number of point gage readings
Q	discharge, cfs
R	hydraulic radius
S_o	slope of flume bottom, ft/ft
S_w	slope of water surface relative to flume bottom, ft/ft
S.F.	shape factor of roughness elements
U	velocity at distance y from boundary, ft/sec
$\overline{U}$	mean velocity along center line of flume, ft/sec
U_*	shear velocity, ft/sec
X	point gage reading, ft
$\overline{X}$	mean point gage reading, ft
y	vertical distance above nominal flow boundary, ft
γ	specific weight of fluid, lb/ft^3
λ	concentration factor

ξ distance beneath top roughness surface to nominal flow boundary, ft

ρ unit mass density; 1.94 slugs/ft^3

σ root-mean-square value of roughness protrusions, ft

τ_o average shear stress at the boundary, lb/ft^2

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
pounds per square foot	4.88243	kilograms per square meter
pounds per cubic foot	16.0185	kilograms per cubic meter
feet per second	0.3048	meters per second
feet per second per second	0.3048	meters per second per second
slugs per cubic foot	515.7957	kilograms per cubic meter
cubic feet per second	0.0283168	cubic meters per second
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.16$.

SUMMARY

Tests were conducted to investigate the characteristics of the vertical velocity distribution in flow in wide channels with large relative roughness. The study was basically a two-dimensional investigation of the boundary roughness effects in turbulent flow. The investigation was conducted in a 48-ft-long, 2-1/2-ft-wide flume with 1/8-, 1/2-, 3/4-, and 1-in. crushed limestone and 3/4-in. concrete cubes as the boundary roughness. Results indicate that the root-mean-square value σ of the boundary roughness heights is related to the Nikuradse equivalent sand grain roughness k_s and that the root-mean-square value can be treated as a roughness parameter for boundaries of densely spaced, irregular, randomly placed roughness elements of uniform size. Appendix A includes the experimental data. Appendix B describes special instrumentation used for measuring the vertical velocity profiles within the flow.

BOUNDARY EFFECTS OF UNIFORM SIZE ROUGHNESS ELEMENTS IN TWO-DIMENSIONAL FLOW IN OPEN CHANNELS

PART I: INTRODUCTION

1. It is commonly assumed that the law of universal velocity distribution applies in open-channel hydraulics; however, difficulties still exist that limit its practical application. The purpose of the study described herein was to investigate the characteristics of the vertical velocity distribution in flow in wide channels that have a large relative roughness. An attempt was made to accurately measure the variables involved in the basic law and to rationalize their effects. A statistical approach for defining the boundary roughness was used in the study, and the results have been correlated with Nikuradse's equivalent sand grain roughness (k_s), Chezy's resistance coefficient (C), and the Darcy-Weisbach friction factor (f) for the roughnesses considered.

2. Keulegan[1] showed that the Prandtl-von Karman universal velocity distribution law for pipe flow could be applied to open-channel flow. Based on a theoretical analysis and an analysis of Bazin's data[2] for rough channels, Keulegan found that the equation

$$\frac{U}{U_*} = 8.5 + 5.75 \log \frac{y}{k_s} \tag{1}$$

described the vertical velocity profile of turbulent flow in a rough channel, where U is the local velocity at a distance y above the flow boundary, U_* is the shear velocity, and k_s is Nikuradse's equivalent sand grain size. Integrating equation 1 over the total depth gives the mean velocity of flow in the form

$$\frac{\bar{U}}{U_*} = 6.25 + 5.75 \log \frac{y}{k_s} \tag{2}$$

where $\bar{U}$ is the mean velocity of flow.

3. Considerable research has been conducted on flow in rough channels since Keulegan published his classical paper in 1938. However, most of it involved the use of artificial blocks, bars, or spherical balls as the channel bottom roughness. Powell[3] experimented with small rectangular sills, Robinson and Albertson[4] used baffle plates, and Moore, Rand, and Hama[5] used transverse bars of various sizes. All of these studies were similar, and Chezy's C was used to describe the flow resistance. Little research has been done on channels with boundary surfaces composed of large-scale natural roughness. The present study was undertaken to provide information on the vertical velocity distribution in turbulent flow in rough, open channels and to seek a better measurement of natural channel roughness than the commonly accepted nominal stone size.

4. The traditional Manning's n lacks a scientific method for prediction and was not employed in the present study. A universal roughness parameter such as Nikuradse's equivalent sand grain diameter k_s may not necessarily be represented by a single dimension of roughness height. Schlichting[6] reported that different distribution patterns of artificial roughness in his laboratory conduit resulted in different values of k_s which were not comparable with the actual dimensions of roughness elements. Recent results from Koloseus and Davidian[7] indicate that a concentration factor (λ) of boundary roughness as well as the geometric properties of individual elements was required for predicting the k_s of a given boundary. At the present time, the λ value can be controlled and approximated only for roughness of uniform shape, size, orientation, and arrangement. A practical parameter of roughness is still required when λ cannot be readily determined. A procedure for describing the roughness characteristics of a boundary surface in terms of the root-mean-square value σ of the surface protrusions is given herein.

5. This report summarizes the results of tests conducted with 1/8-, 1/2-, 3/4-, and 1-in.* crushed limestone rock and 3/4-in. concrete cubes as the channel bed roughness. Size identification of the crushed stone is the minimum sieve size upon which the particles were retained during screening

* A table of factors for converting British units of measurement to metric units is presented on page xi.

operations. The square mesh openings of the sieve that passed the test rock were 1/4 in. larger than those that retained it. The 1/8-in. size passed the No. 4 sieve and was retained on the No. 8 sieve. Three interim reports[8,9,10] published on the study include all the data except for the 1/8-in. stone and 3/4-in. concrete cubes. All the test data are presented herein in Appendix A.

PART II: TEST APPARATUS

Description of Test Facility

6. The general layout of laboratory equipment is shown in fig. 1. The recirculating flow system consisted of the sump, the pump, the supply pipes, the headbay, and the flume. The test flume, 48 ft long, 2-1/2 ft wide, and 1-1/2 ft deep, was of steel construction and equipped with a sensitive, electrically operated tilting mechanism. The slope range was from a maximum slope of 0.015 to a maximum adverse slope of -0.005. The reference datum for vertical measurements consisted of two rails mounted on the flume sidewalls parallel to the flume bottom. The test section was 38.5 ft downstream from the flume entrance, at a location where the turbulent boundary layer was considered to be fully developed. Approximately uniform depth in the flume was obtained by adjusting a chain-driven, undershot tailgate. The supply pipe consisted of a 10-in. main with a 10- by

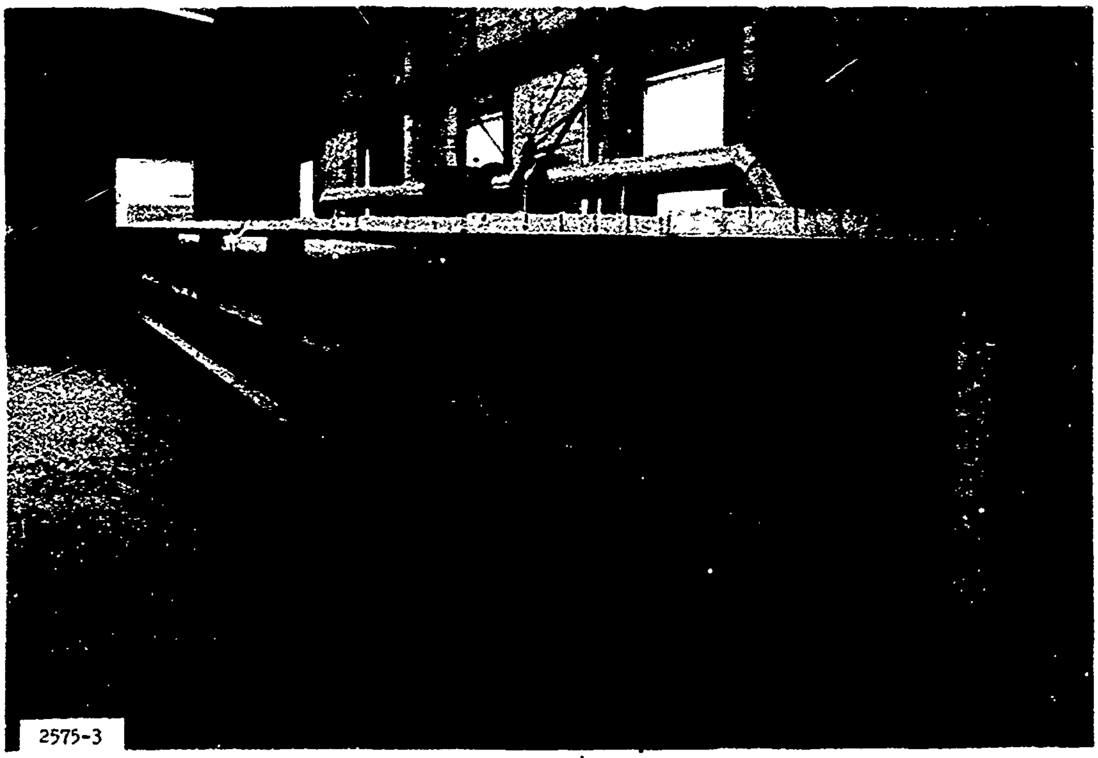


Fig. 1. View of test flume, looking downstream

5-in. venturi tube and a 6-in. bypass with a 6- by 3-in. venturi tube. The venturi tube pressure differentials were read by means of a mercury U-tube manometer. Discharge was controlled by valves located between the venturi meters and the flume headbay.

Equipment

7. Various commercial and homemade pitot tube and manometer systems were used in an effort to obtain optimum velocity measurements. The inability to repeat measurements greatly reduced the reliability of such systems, especially in measuring the low flow velocities. The most reliable pitot tube-manometer system was a 5/16-in.-OD, commercial, Prandtl-type pitot tube and a shopmade, 1:10-sloping manometer (fig. 2). Velocity data with the 1/2- and 1-in. stone and the 3/4-in. cubes as the boundary roughness were obtained using this equipment. Initially the system required a long settling period between readings and frequently produced unsatisfactory variations in the velocity when checks were made at

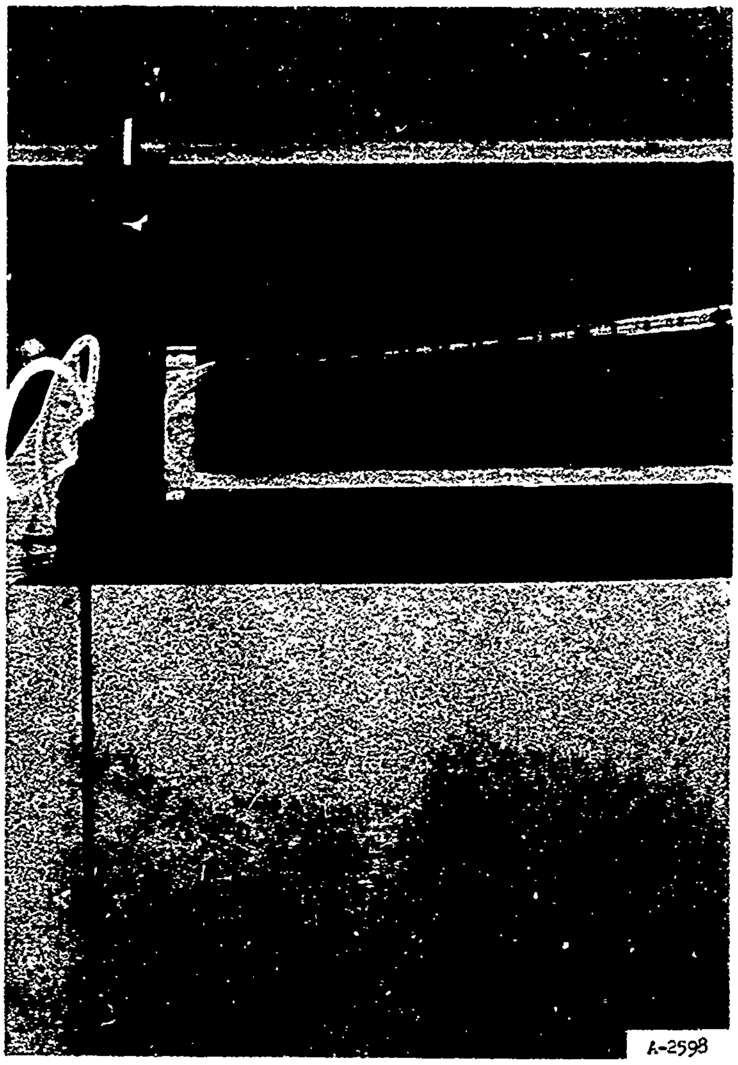


Fig. 2. 5/16-in. pitot tube and sloping manometer

arbitrary locations in the profile. Both instrument response and measurement repeatability were improved by injecting several drops of an aerosol solution into the water column of the inclined manometer. The instrument was calibrated in a 14-ft-diam rotating calibration tank; the basic calibration curve is shown in plate 1.

8. Improved accuracy in the velocity measurement was made with the use of a variable-reluctance differential pressure transducer in conjunction with a 1/8-in. pitot tube. A complete description of the instrument, calibration, and operating procedure is given in Appendix B.

PART III: TEST CONDITIONS AND PROCEDURES

Establishment of Test Flow

9. The basic ideal requirements for establishing the test flow were to: (a) obtain uniform flow over sufficient flume length, and (b) maintain two-dimensional flow in the flume within practical limits. Exactly uniform flow could not be expected, principally because of insufficient flume length for the resistance and gravity forces to balance each other. However, relatively uniform flow was obtained by carefully setting the flume tailgate. Adjustments were also made in the analytical procedure when the flow appreciably deviated from the general assumption of uniformity. This adjustment is described in paragraph 21. Flows at a small Froude number were desirable to minimize instabilities resulting from surface waves.

10. Two-dimensional flow can only be assumed with flows at large width-to-depth ratios. The present tests were limited to ratios between 5 and 10, which corresponded to flow depths of 0.5 to 0.2 ft, respectively. Within this range, the following criteria were obtained: (a) the relative roughness became large, (b) the Froude number was less than unity, and (c) sidewalls and secondary currents had negligible effect upon the centerline velocity profile.

Discharge and Bed-Slope Adjustment

11. Selections of discharges and flume slopes were arbitrary, providing they did not produce depths that would not conform to the criteria in paragraph 10. The slopes used were 0.0023, 0.0030, 0.0040, and 0.0060. The minimum slope was governed by the sensitivity of velocity measuring equipment and the possibility of the proportionally greater error involved in determining the energy gradient. The maximum slope depended upon the Froude number of the flow, which was related to the surface stability at the desired width-depth ratio. The discharge varied from 0.75 to 2.50 cfs in order to meet the required depth at the selected bed slope.

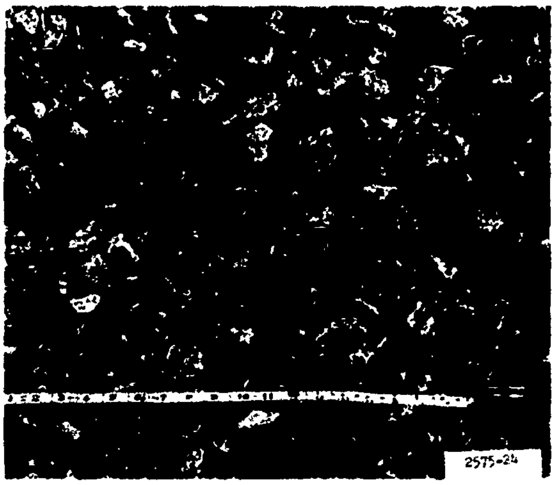
Vertical Velocity Profiles

12. The primary interest of the study was the vertical velocity distribution for fully developed, turbulent, two-dimensional, uniform flow. Therefore, at the beginning of testing it was necessary to select the proper location in the flume where these conditions were most nearly fulfilled. Selection of the location, 38.5 ft from the channel entrance and hereafter called the test section, was based on the results of detailed velocity traverses taken at several locations along the length of the flume. The velocity traverses indicated that symmetrical flow conditions existed in the flume. Plate 2 shows that potential flow generally existed at the flume entrance and that the flow at the test section was symmetrical and the turbulent boundary layer fully developed. Detailed vertical velocity profiles were measured at the center line. Measurements in the vertical were generally made at intervals of 0.02 ft near the boundary and at larger intervals near the free surface. The higher velocities measured at a slope of 0.0060 were obtained by extrapolating the pitot tube calibration curve.

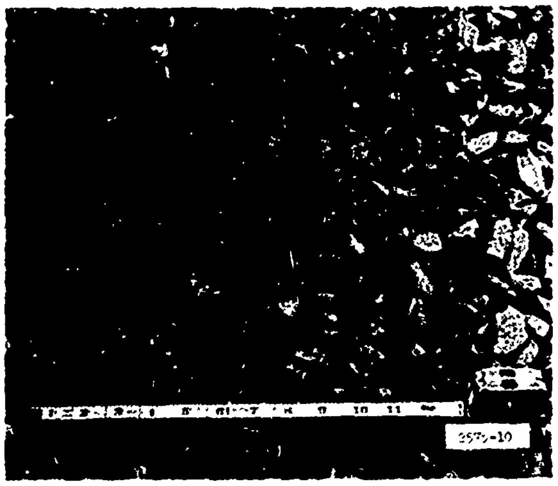
Boundary Roughness

13. Tests were conducted with four different uniform sizes (1/8, 1/2, 3/4, and 1 in.) of crushed limestone rock and one size (3/4 in.) of concrete cubes (see fig. 3); size identification is described in paragraph 5. The crushed stone (except the 1/8-in. stone, which will be described later) was initially placed and spread in the flume with shovels. No attempt was made to spread the stone at a prescribed thickness, but generally the average thickness was about twice the nominal stone diameter. In accordance with the requirement for uniform flow, the stone layer was carefully leveled with reference to still-water surface. The flume was positioned horizontally and flooded to a depth at which the water surface was level with the highest stone protrusions. A mason's trowel was used to level and lightly compact the layer with reference to the water surface.

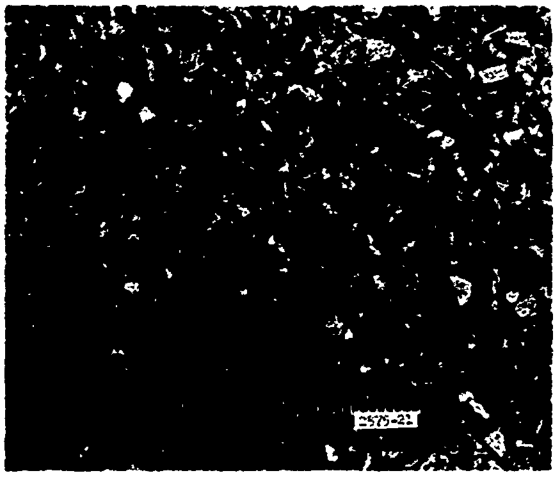
14. The 1/8-in. stone was cemented to the flume bottom with a



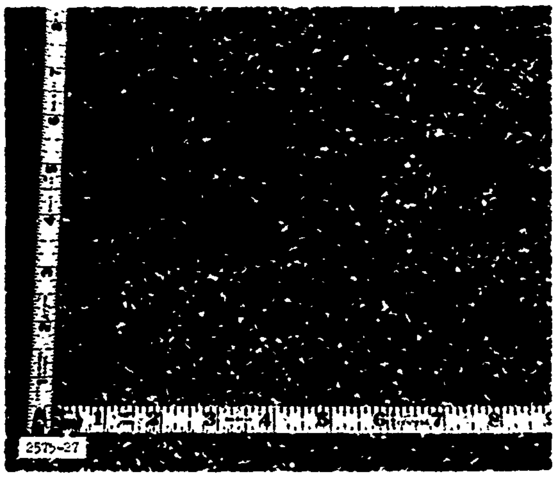
a. 1-in. stone



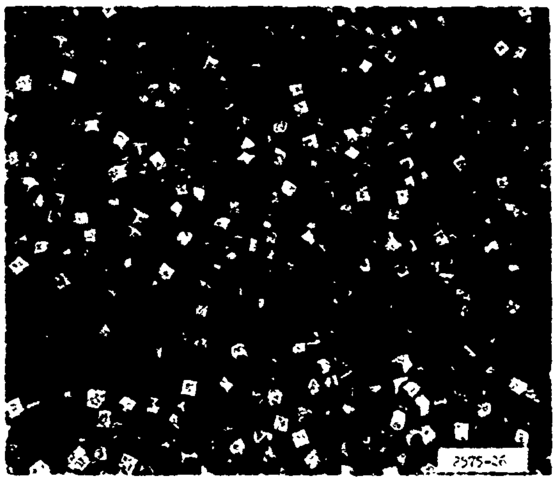
b. 3/4-in. stone



c. 1/2-in. stone



d. 1/8-in. stone



e. 3/4-in. cubes

Fig. 3. Flume bed roughness

plastic adherent to prevent displacement at the higher discharges. The flume bottom was coated with a thin layer of adherent, and the stone was evenly spread to a layer thickness of approximately twice the nominal stone diameter. The loose particles were "washed out" after the adherent hardened.

15. The 3/4-in. concrete cubes were placed upon a layer of 3/4-in. stone to obtain the desired irregular surface (fig. 3e), and the surface was leveled as described in paragraph 13.

16. Determination of the stone characteristics given in the tabulation on page 15 for each stone size was made from measurements of 100 randomly selected stones. Small shovelfuls of stone were obtained from several locations within the flume or from the stockpile and placed into one sample. The large sample was quartered into sixteen test specimens, ten of which were randomly selected and the remaining six discarded. A small box was constructed in which the bottom was divided into a 10 by 10 grid (100 small squares). Each square was assigned a number, and each number was recorded on a separate piece of paper which was placed in a container. One of the ten test specimens was placed in the box and spread until each square was occupied by a stone particle. The excess particles were removed. Ten numbers were drawn from the container and the particles occupying the corresponding numbered squares were selected. Consequently, ten particles selected from each of the ten specimens produced 100 stones for measurement. Because of the small variation in size and shape of the 1/8-in. stone, the 100 particles were randomly selected by hand from the stockpile.

17. Two methods for determining the effective roughness height of the boundary roughness were investigated. The first method involved measuring the three axial diameters of stone samples from which the average diameter D_{50} and shape factor S.F. were computed. The bar graphs in plates 3-6 indicate the mean diameters and shape factors for each size of test stone. The 100 randomly selected stones (paragraph 16) were measured with a hand caliper, and the mean diameter D_{50} for each stone size was computed according to the equation:

$$D_{50} = 2(abc)^{1/3} \quad \text{(reference 11)} \tag{3}$$

where a , b , and c are the three axial radii of the stone. The shape factor S.F. is defined as

$$S.F. = \frac{c}{\sqrt{ab}} \quad \text{(reference 12)} \tag{4}$$

where $a > b > c$.

18. The second method involved measuring the surface roughness resulting with the test stone in place. The roughness characteristics are expressed in terms of the root-mean-square value σ of the surface protrusions. Approximately 800 point gage readings of the boundary surface taken at 0.3-in. intervals on six 3- by 3-in. areas were obtained and analyzed for each bed roughness, using the equation

$$\sigma = \sqrt{\frac{\Sigma(X - \bar{X})^2}{N - 1}} \tag{5}$$

where X is the point gage reading, $\bar{X}$ is the mean point gage reading, and N is the number of readings. The root-mean-square value σ for the 1/8-in. stone was determined from a sample plate using a surface profile analyzer (fig. 4). Nine hundred readings were taken at intervals of 0.01 ft.

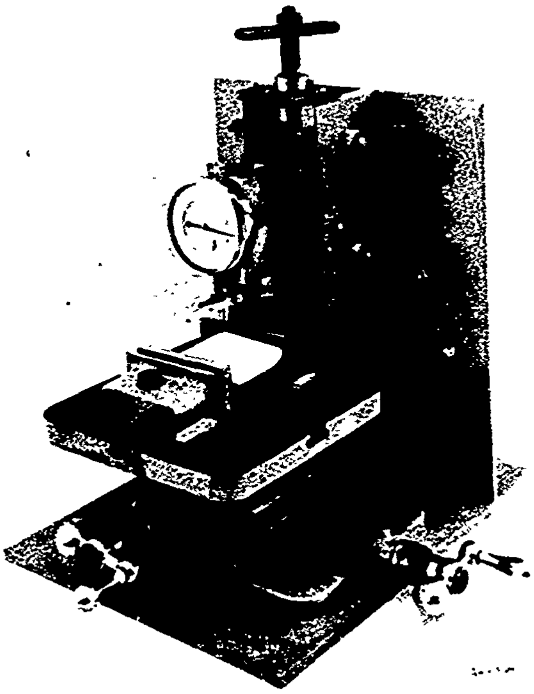


Fig. 4. Surface profile analyzer

19. In general, the excessively deep interstices in the development of the surface profiles were omitted. It was believed that the very deep interstices would have negligible effects upon the local flow conditions. An attempt

was made to evaluate the effects of these omissions on the σ value. This was accomplished by first arranging the measured readings in numerical sequence. The σ values were successively computed using a predetermined percentage increase in the number of readings omitted. Each computed value was divided by the σ value resulting (using all the data) and plotted as a function of the percentage of total data points used. Typical measured profiles are shown in plate 7, and the results of this statistical study are shown in plate 8. Reasonable correlation of all surfaces was obtained except that resulting with the 3/4-in. stone. Plate 8 indicates the general relation between the successive elimination of the deeper interstices and the resulting σ.

Evaluation of Shear Velocity

20. Shear velocity is defined by

$$U_* = \sqrt{\frac{\tau_o}{\rho}} \tag{6}$$

where ρ is the unit mass density of the fluid and τ_o is the boundary shear stress. For steady, two-dimensional, uniform flow, τ_o can be determined by the equation:

$$\tau_o = \gamma d S_o \tag{7}$$

and therefore

$$U_* = \sqrt{dgS_o} \tag{8}$$

where d is the corrected flow depth, γ is the specific weight of the fluid, g is the gravitational acceleration, and S_o is the slope of flume bed or piezometric gradient for uniform flow.

21. The water-surface profile was measured with a standard point gage which could be read to 0.001 ft by means of a vernier scale. Measurements were taken at 1- to 2-ft increments from a distance approximately

20 ft upstream to about 4 ft downstream of the test section. In certain cases, when the mean slope of the water surface differed from the flume slope, the following modified form of equation 8 was used:

$$U_* = \sqrt{gd\,(S_o + S_w)} \tag{9}$$

where S_w is the slope of the water surface relative to the flume bottom and it may have a positive or negative value. Equation 9 was derived assuming a hydrostatic pressure distribution because S_w is small compared to S_o.

Determination of Theoretical Flow Boundary

22. The determination of the effective datum for vertical ordinates is of considerable significance because of the large relative roughness used in the study. Neither the bottom of the flume nor the top stone surface can be considered as the effective datum of flow. Initially, this datum was assumed to be located at a distance $D_{50}/2$ beneath the top surface of roughness. A second procedure assumed the effective boundary to be located at a distance σ beneath the top surface of roughness. A third procedure was recommended by Mr. F. F. Escoffier, WES hydraulic consultant.

23. Mr. Escoffier's procedure assumes that

$$y = h + \xi$$

where y is the vertical ordinate of the point velocity in the flow, h is the distance between this position and the top of the stone surface, and ξ is the distance beneath the stone surface to the theoretical flow boundary. Plate 9 shows the schematic relation of σ, ξ, k, h, y, and d and the ideal velocity profile. The following relation is obtained using the universal velocity distribution law for rough boundary:

$$h + \xi = \frac{k_s}{30} \exp\left(\frac{0.4\,U}{U_*}\right) \tag{10}$$

When the measured h is plotted against the value of $\exp\left(\frac{0.4\ U}{U_*}\right)$ in Cartesian coordinates, either ξ or k_s can be determined graphically for a specific set of data. A detailed illustrated example of the procedure is given in plate 10.

Nikuradse's Equivalent Roughness Height (k_s)

24. Nikuradse's equivalent roughness height can be approximated from the velocity measurements based on equation 2, which can be transposed into the following:

$$k_s = \log^{-1}\left(1.08 + \log d - 0.174\,\frac{\bar{U}}{U_*}\right) \tag{11}$$

where

d = depth of flow to effective flow boundary

$\bar{U}$ = mean velocity along center line of flume and also

$$\bar{U} = \frac{1}{d}\int_0^d U\,dy\ ;\ U \text{ is the local mean velocity at } y$$

U_* = shear velocity

The mean velocity $\bar{U}$ for this study was determined by graphically integrating the velocity profile for each test.

PART IV: RESULTS AND DISCUSSION

Boundary Roughness

Stone characteristics

25. The actual surface configurations of the five boundaries are shown in fig. 3. The bar graphs in plates 3-6 indicate the mean diameter and shape factor for each size of stone based on random sampling. The mean diameter D_{50}, shape factor S.F., and corresponding σ value are summarized in the following tabulation:

	Stone Size, in. 1/8	1/2	3/4	1	3/4-in. Cube
S.F.	0.620	0.460	0.485	0.510	1.000
D_{50}, ft	0.01036	0.055	0.080	0.106	0.083
σ, ft	0.00360	0.0148	0.0181	0.0272	0.0236
k, ft	0.0072	0.0296	0.0362	0.0544	0.0472
k/D_{50}	0.695	0.538	0.452	0.513	0.569

The mean shape factor for three of the four stone sizes tested is approximately 0.5. The higher value for the 1/8-in. stone is attributed to the small variation between the three axial diameters. In fact, differentiation between the three diameters was often difficult. The ratio of the effective roughness height k ($k = 2\sigma$) to D_{50} is relatively constant except for the 1/8-in. stone. However, the same relation may not exist among other types and gradations of roughness elements.

k, k_s, and ξ

26. Determination of k_s and ξ according to equation 10 is illustrated in plate 10. The accuracy of the results using this procedure depends upon the measured and computed values of U and U_*, respectively. The ratio ξ/σ as shown in the following tabulation varies appreciably, but excluding the 1/8-in. stone, the average value is about 1.21, which is close to the assumption for ξ/σ used in the initial procedure (paragraph 22). The average ξ/σ value for the 1/8-in. stone is about 3.5. Indications are that the concentration or distribution of roughness

Rock Size in.	Slope	Discharge cfs	$\overline{U}$ fps	U_* fps	d ft	k_s† ft	k_s†† ft	$\frac{k_s}{k}$††	$\frac{\xi}{\sigma}$
1	0.0023	1.50	1.495	0.174	0.407	0.156	0.155	2.88	0.27
	0.0023	1.75	1.631	0.181	0.444	0.147	0.152	2.80	0.42
	0.0023	2.00	1.687	0.192	0.497	0.177	0.192	3.54	0.94
	0.0040	2.00	2.017	0.232	0.417	0.154	0.175	3.22	1.08
	0.0040	2.50	2.217	0.252	0.493	0.174	0.206	3.72	1.05
	0.0060	2.50	2.658	0.294	0.446	0.143	0.202	3.70	1.65
3/4	0.0023	1.00	1.281	0.159	0.341	0.155	0.212	5.86	2.77
	0.0023	1.50	1.587	0.171	0.394	0.122	0.127	3.51	1.83
	0.0040	1.75	2.029	0.222	0.370	0.109	0.135	3.73	1.71
	0.0060	2.00	2.313	0.270	0.378	0.138	0.164	4.53	1.59
1/2	0.0023	1.25	1.456	0.159	0.339	0.100	0.104	3.49	0.56
	0.0023	1.75	1.581	0.182	0.445	0.165	0.174	5.85	2.06
	0.0040	1.75	1.915	0.215	0.359	0.114	0.126	4.25	1.75
	0.0060	1.75	2.459	0.247	0.315	0.070	0.084	2.84	1.32
1/8	0.0023	0.75	1.509	0.127	0.217	0.022	0.024	3.26	2.78
	0.0023	1.50	1.925	0.150	0.305	0.021	0.024	3.32	4.86
	0.0030	1.25	1.969	0.159	0.263	0.022	0.024	3.29	3.61
	0.0040	1.00	2.009	0.164	0.208	0.018	0.019	3.64	2.59
3/4 cubes									
	0.0023	1.50	1.459	0.173	0.406	0.168	0.185	3.92	0.72
	0.0030	1.75	1.707	0.197	0.402	0.150	0.164	3.47	0.68
	0.0040	1.75	1.877	0.218	0.369	0.141	0.151	3.20	0.76
	0.0040	2.00	2.026	0.228	0.405	0.139	0.143	3.03	0.64

† From equation 11.
†† From equation 10.

elements may have an important effect upon the location of the theoretical or nominal flow boundary. As previously noted, the 1/8-in. stone layer was essentially one layer thick while the other test material layers were some multiple of the mean particle diameter. Also, the 3/4-in. concrete cubes were placed upon a bed of 3/4-in. stone. Morris[13] has suggested that the interstices between the roughness elements for densely packed particles will be filled with dead water containing stable eddies, creating a pseudo-wall and pushing the nominal flow boundary near the top surface of the roughness elements. The single layer roughness has less ability to maintain any dead water, and the boundary will be lowered. Test results from

this study appear to support this hypothesis, but more experimental studies are necessary to substantiate it.

27. Results from the study on boundary roughness in which the roughness elements were closely spaced in a random pattern indicate that the Nikuradse equivalent sand grain roughness size k_s is proportional to the measured σ value. In this case, the root-mean-square roughness as well as k_s could be considered universal. The ratio of k_s/k varied between 2.8 and 4.5 except for results for a slope of 0.0023 and a discharge of 1.75 cfs on 1/2-in. stone and 1.00 cfs on 3/4-in. stone. The average value is about 3.5 when these two sets of data are eliminated. Information obtained from other investigations has been studied and the results are tabulated below along with those from the present study.

Type of Roughness	σ, ft	k_s, ft	k_s/k	Source of Data
Hemisphere	0.0338	0.225	3.33	Einstein[14]
3/16-in. cube with 3/8-in. spacing	0.00676	0.0526	3.88	Koloseus[7]
Chute spillway	0.00091	0.00642	3.53	Huval[15]
Conduit	0.000363	0.00166	2.30	WES[16]
Wire screen			2.50	Hama[5]
Sphere	0.0024	0.0101	2.08	Schlichting[6]
Spherical segment	0.00347	0.01435	2.08	Schlichting[6]
Uniform size crushed limestone	Page 15	Page 16	3.5	Present study

Velocity Distribution

28. All the test velocity data except the two sets of data discussed in paragraph 27 were analyzed and are presented in nondimensional plots in plates 11-15. The data were analyzed in terms of both $y = h + 0.9\,\sigma$ and $k_s = 3.3\,k$. The straight lines on these plates are for the equation $\frac{U}{U_*} = 5.75 \log \frac{y}{k_s} + 8.5$. Data scatter in certain instances is attributed to instrument limitations. Surface waves in the flow could also be a contributing factor. Adjacent to the solid boundary, the actual measured velocities are larger than the theoretical value indicated by the equation

$\frac{U}{U_*} = 5.75 \log \frac{y}{k_s} + 8.5$. Detailed study of velocity distribution close to the boundary surface would be desirable.

Resistance Coefficients

29. The most commonly used resistance coefficients are the Chezy C , the Darcy-Weisbach f , and the Manning n . These are related to the ratio of the mean velocity to the mean shear velocity by the following expressions:

$$C = \sqrt{g}\left(\frac{\overline{U}}{U_*}\right) \tag{12}$$

$$f = 8\left(\frac{U_*}{\overline{U}}\right)^2 \tag{13}$$

$$n = \frac{1.486}{\sqrt{g}} R^{1/6}\left(\frac{U_*}{\overline{U}}\right) \tag{14}$$

Plate 16 illustrates the similarity between the Prandtl-von Karman equation for pipe flow and Keulegan's open-channel flow equation. The data generally plotted between the lines generated by the two equations.

PART V: CONCLUSIONS AND COMMENTS

30. The following conclusions, and comments thereon, were drawn from the study:

a. The characteristic velocity distribution for two-dimensional channel flow at relative roughness d/k of 8 or more appears to be universal. The semiempirical formula $U/U_* = 5.75 \log y/k_s + 8.5$ can be applied except for velocities very close to the boundary where the actual velocity is greater than the theoretical value.

b. The root-mean-square value σ of rough surface protrusions is related to the Nikuradse roughness height k_s and can also be treated as a roughness parameter for boundaries formed by uniform size roughness elements closely spaced in a random pattern. The condition should be limited to cases in which the boundary is hydrodynamically rough. This conclusion should not be applied to boundaries that are classified as hydrodynamically wavy.

c. The location of the theoretical flow boundary beneath the top of roughness protrusions does not appear to be constant. The datum for the boundary roughness in which the stone layer thickness was more than one diameter is located at a distance of about 0.9 to 1.0 σ . The distance was close to the mean stone diameter for the roughness that was only one layer thick. Additional tests are necessary to evaluate the effect the interstices in the multilayer roughness might have on the location of the theoretical flow boundary.

d. The characteristic velocity distribution appears to be independent of absolute size and shape of the uniformly graded material constituting the boundary roughness and of the bed slope, discharge, and flow depth.

e. The present study was limited to boundary roughnesses resulting with essentially uniform size roughness elements. The test results indicate that the relation between k_s and σ is independent of the stone size and geometry as long as the roughness elements are continuous and placed in a random manner. The effect of stone gradation such as that used for riprap is recommended for a future study.

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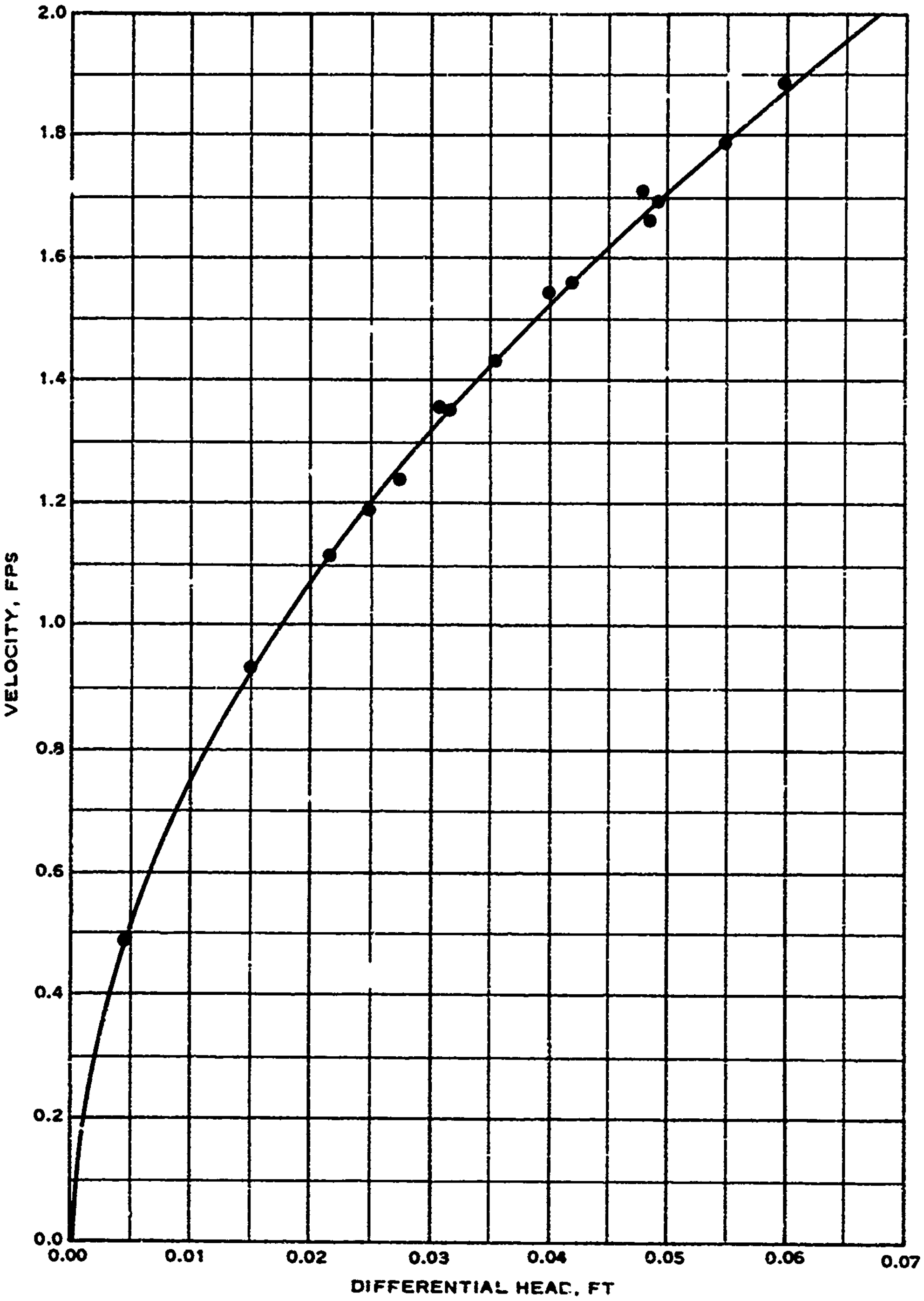
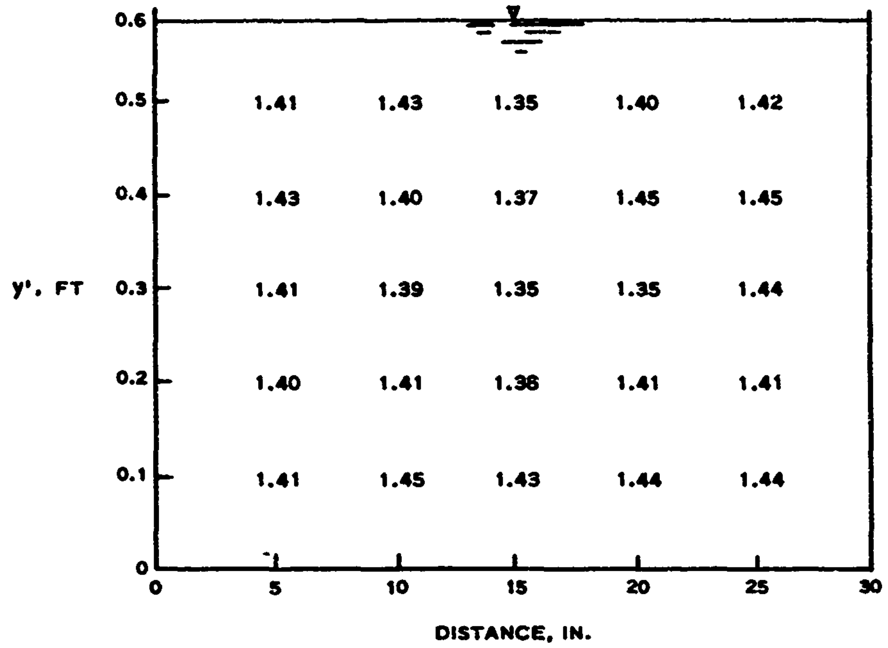


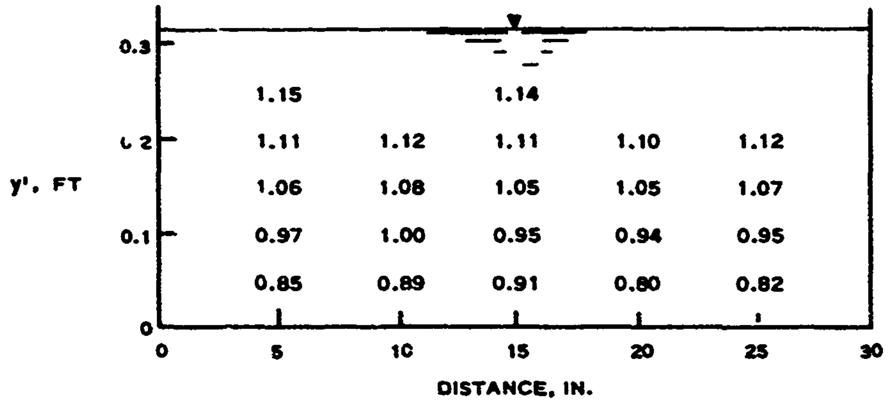
CALIBRATION CURVE
5/16-INCH PITOT TUBE
SLOPING MANOMETER
WITH AEROSOL

PLATE I



DISTRIBUTION IN FLUME ENTRANCE,STATION 0+00

Q = 1.80 CFS



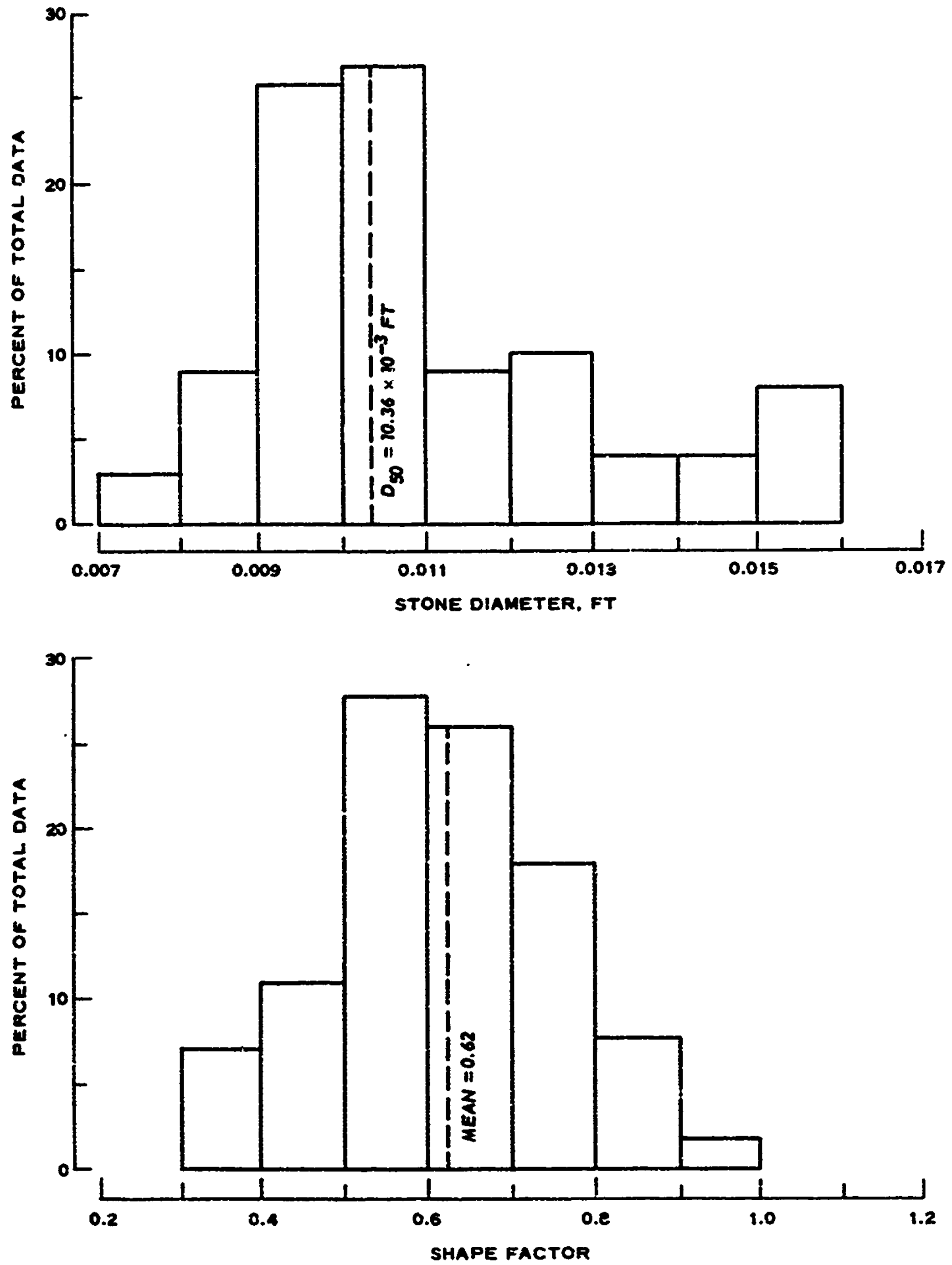
DISTRIBUTION AT TEST STATION 0+38.5

Q = 0.75 CFS

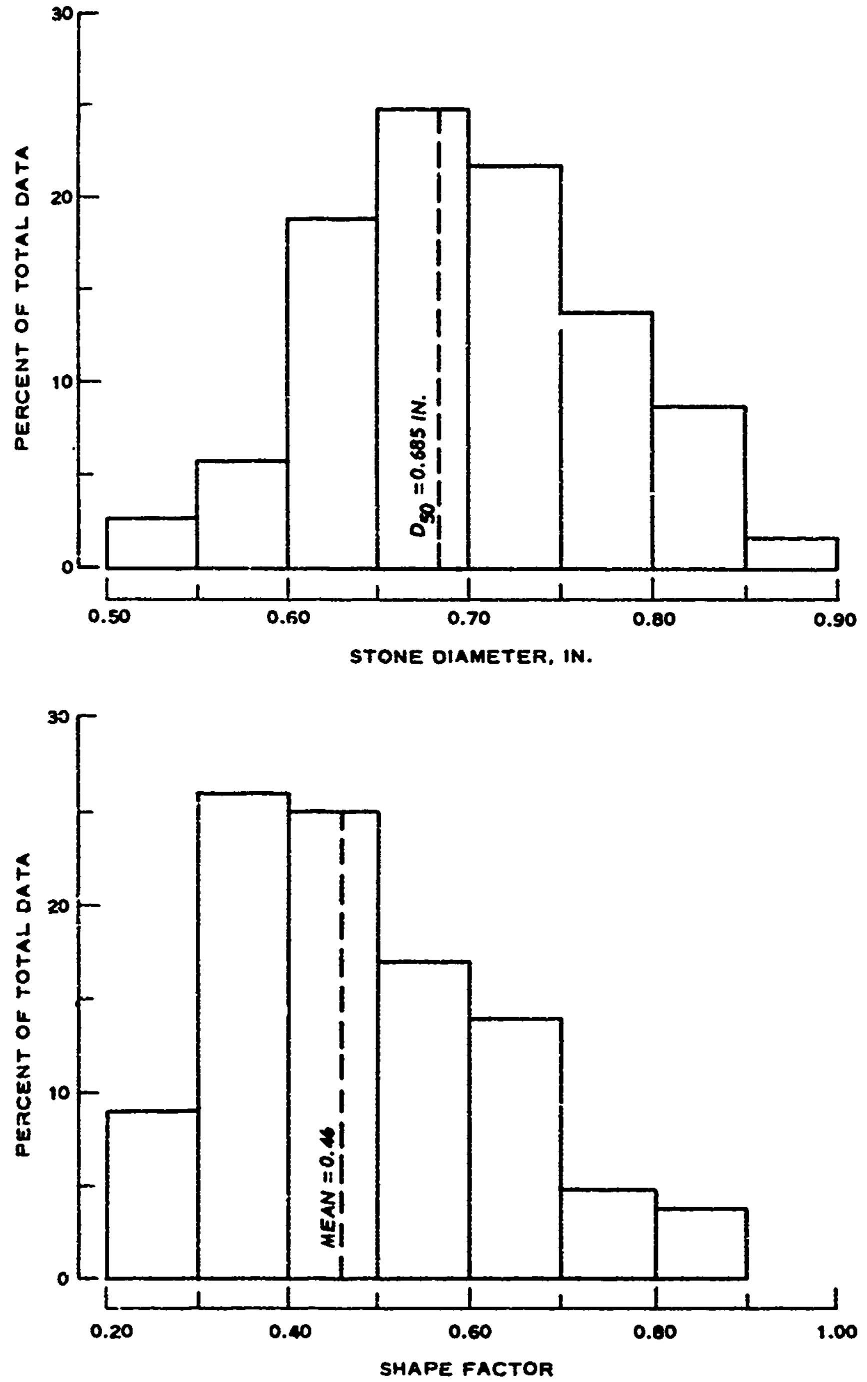
NOTE: ALL VELOCITIES ARE IN FEET PER SECOND. y' IS THE DISTANCE FROM THE TOP OF THE STONE.
SCALE DISTORTION, 3.13 VERTICAL TO 1.0 HORIZONTAL.

TYPICAL TRANSVERSE VELOCITY DISTRIBUTIONS

3/4-INCH STONE



STONE CHARACTERISTICS
NOMINAL STONE SIZE = 1/8 INCH
100 SAMPLES

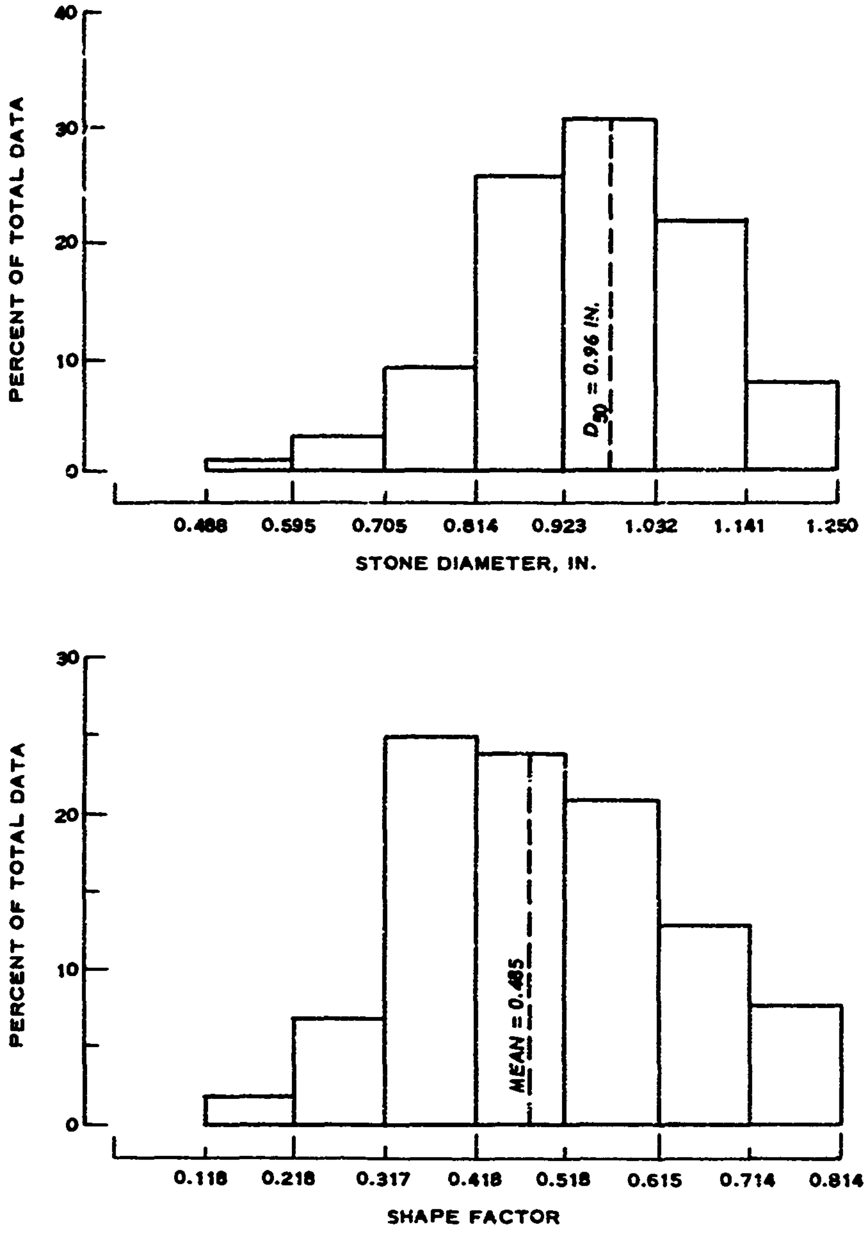


STONE CHARACTERISTICS

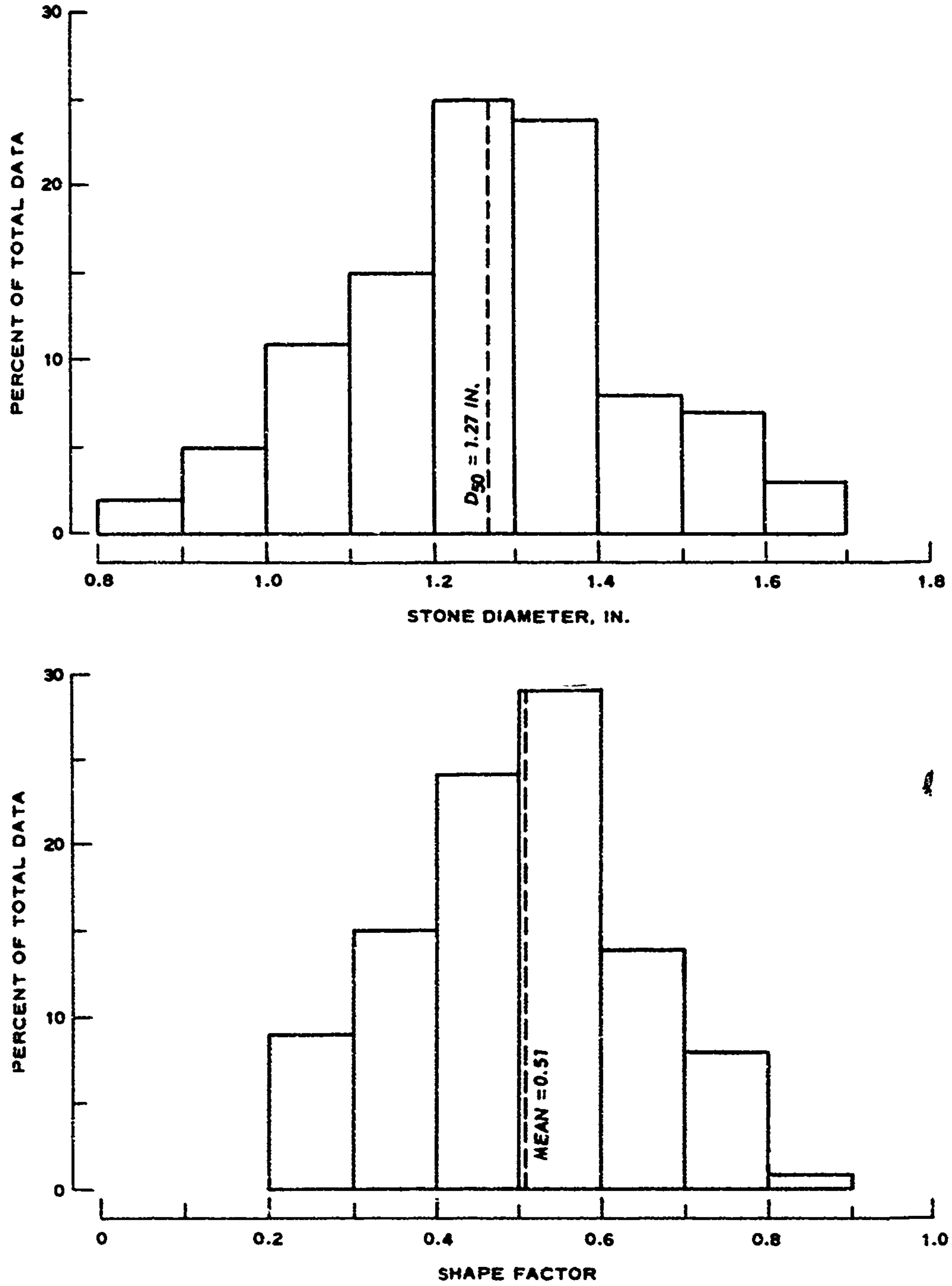
NOMINAL STONE SIZE = 1/2 INCH

100 SAMPLES

PLATE 4

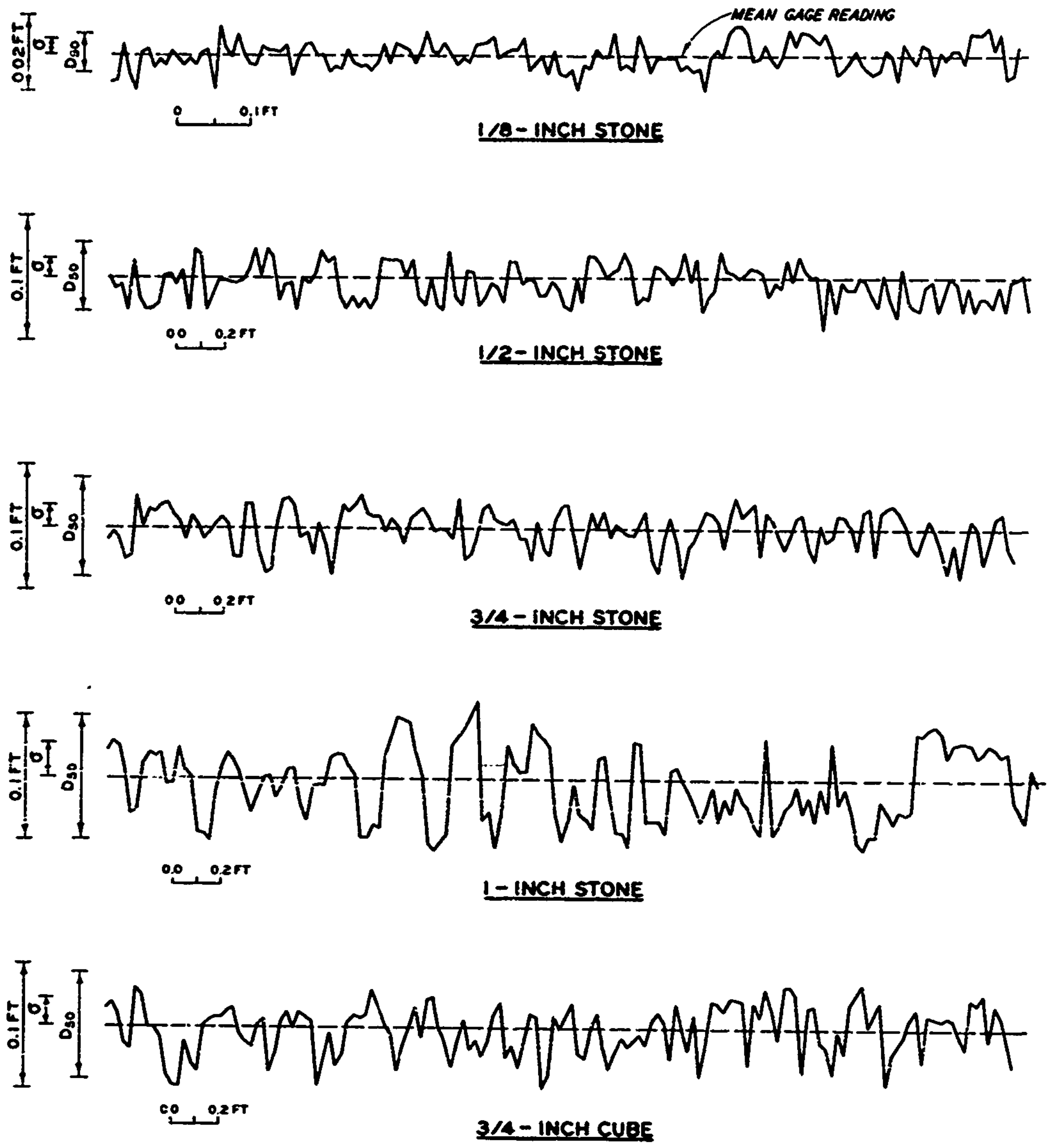


STONE CHARACTERISTICS
NOMINAL STONE SIZE = 3/4 INCH
100 SAMPLES



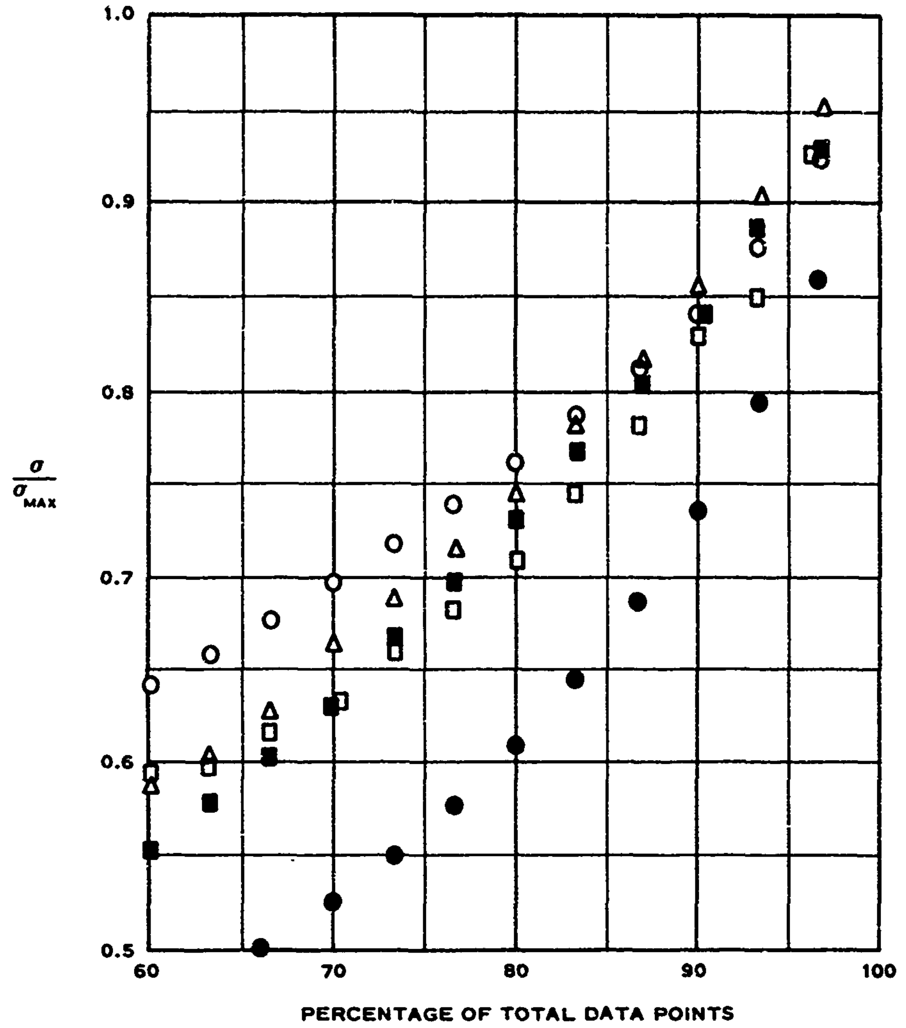
STONE CHARACTERISTICS
NOMINAL STONE SIZE = 1 INCH
100 SAMPLES

PLATE 6



STONE SIZE, IN.	HORIZONTAL MEASUREMENT INCREMENT, IN.	D_{50} SIZE, FT	σ, FT
1/8	0.12	0.01036	0.0036
1/2	0.30	0.055	0.0148
3/4	0.30	0.080	0.0181
1	0.30	0.106	0.0272
3/4 CUBE	0.30	0.083	0.0236

ROUGHNESS SURFACE PROFILE



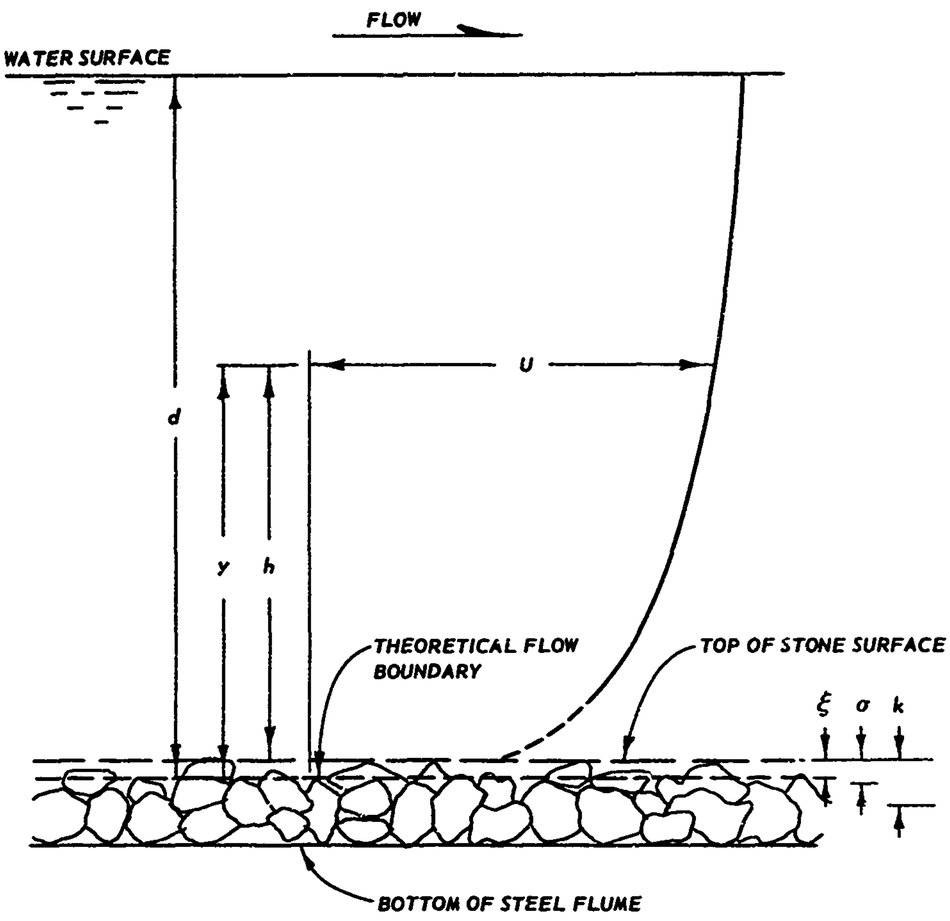
LEGEND

SYMBOL	STONE SIZE, IN.	TOTAL NO. DATA POINTS
○	1/8	900
△	1/2	814
●	3/4	759
■	1	836
□	3/4 CUBE	726

NOTE: σ = ROOT-MEAN-SQUARE VALUE WITH SPECIFIED PERCENTAGE OF POINTS OMITTED

σ_{MAX} = ROOT-MEAN-SQUARE VALUE TO INCLUDE ALL THE DATA POINTS

ROOT-MEAN-SQUARE ANALYSIS



LEGEND

$y = h + \xi$

$\sigma = \sqrt{\dfrac{\Sigma(x - \bar{x})^2}{n - 1}}$

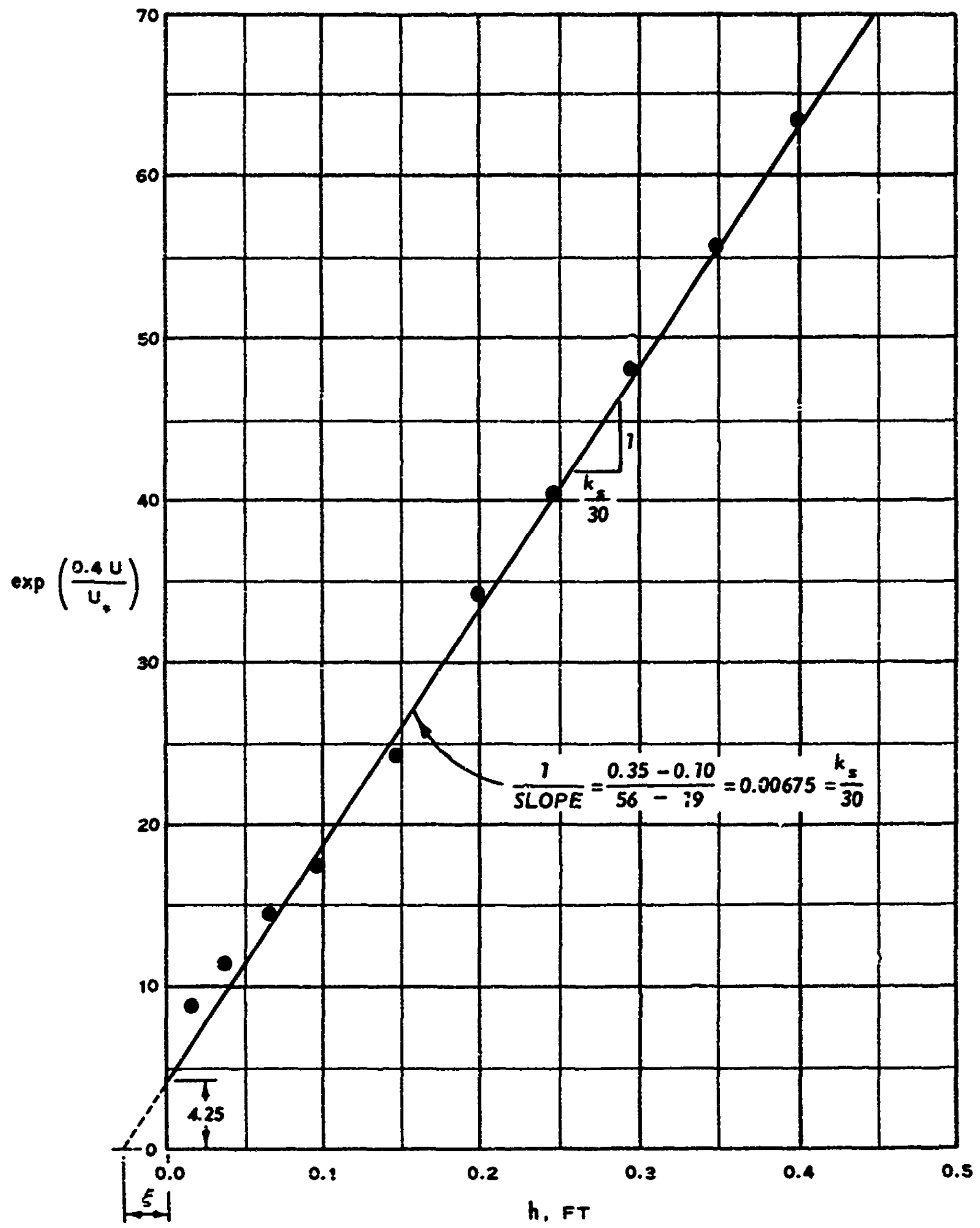
$k = 2\sigma$

$\xi \approx 0.9\sigma$

X = POINT GAGE READING ON STONE SURFACE

N = NUMBER OF READINGS

DEFINITION SKETCH OF PARAMETERS



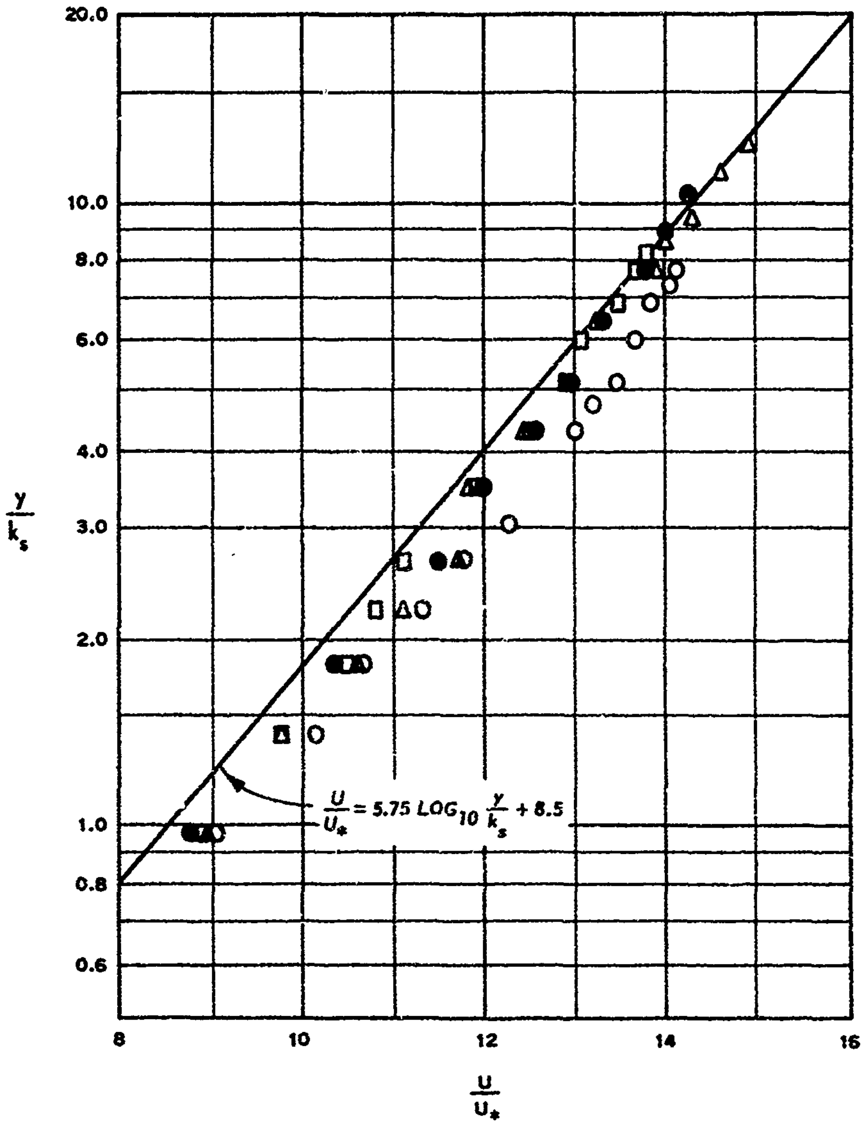
BASIC EQUATION:

$$h + \xi = \frac{k_s}{30} \exp\left(\frac{0.4\,U}{U_*}\right)$$

$k_s = 30 \times 0.00675 = 0.206$ FT

$\xi = 4.25 \times 0.00675 = 0.0287$ FT

k_s AND ξ
SAMPLE COMPUTATION
ESCOFFIER METHOD
Q = 2.50 CFS, $S_0 = 0.004$
1-INCH STONE

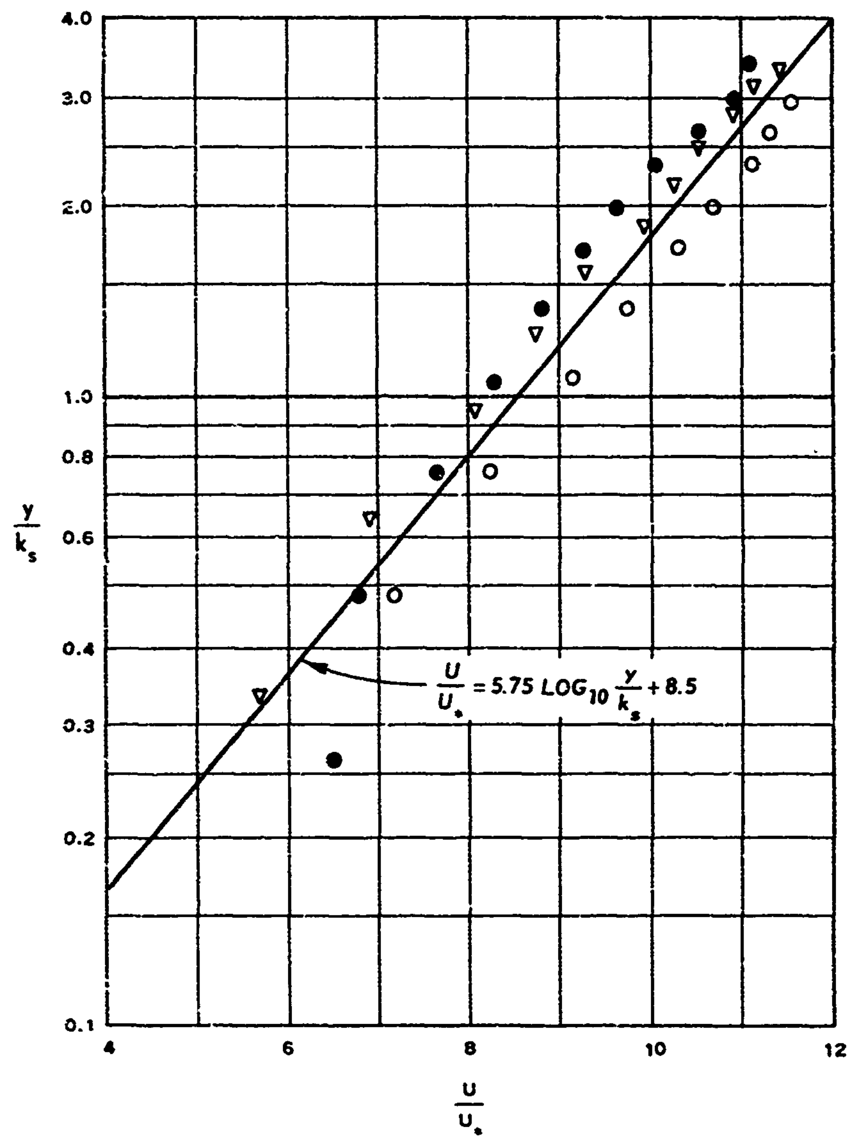


LEGEND

	Q, CFS	SLOPE	$\bar{U}$, FPS
□	0.75	0.0023	1.509
●	1.25	0.0030	1.969
Δ	1.50	0.0023	1.925
O	1.00	0.0040	2.009

NONDIMENSIONAL VERTICAL VELOCITY PROFILE

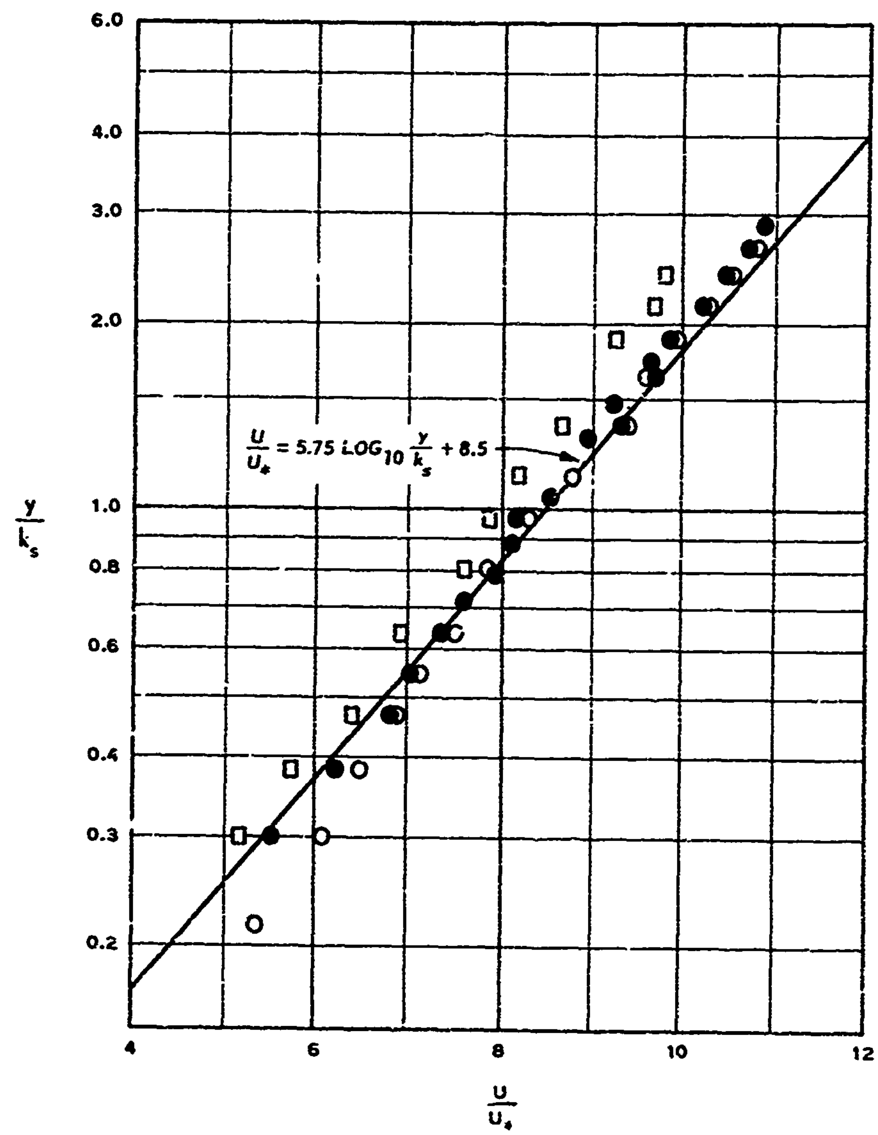
1/8-INCH STONE



LEGEND

	Q, CFS	SLOPE	$\bar{U}$, FPS
∇	1.25	0.0023	1.46
●	1.75	0.0040	1.92
O	1.75	0.0060	2.46

NONDIMENSIONAL
VERTICAL VELOCITY PROFILE
1/2-INCH STONE

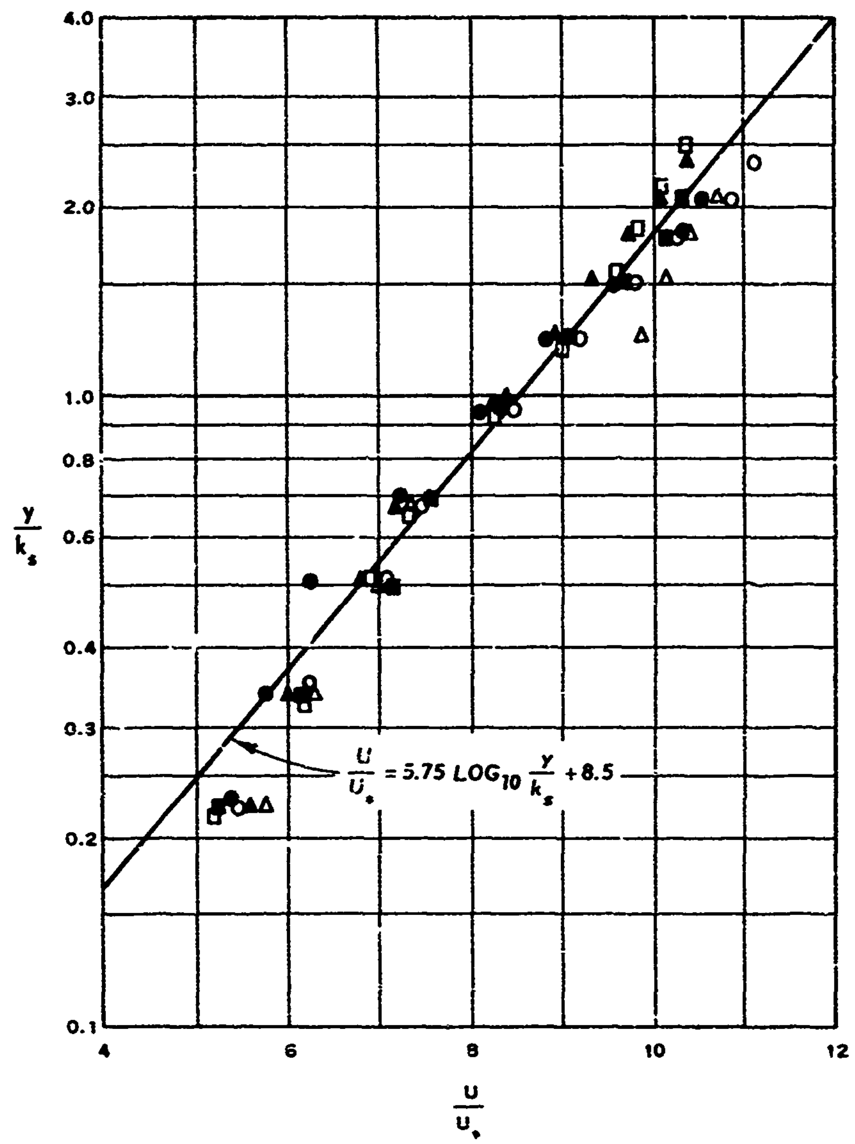


LEGEND

	Q, CFS	SLOPE	$\bar{U}$, FPS
●	1.50	0.0023	1.59
○	1.75	0.0040	2.03
□	2.00	0.0060	2.31

NONDIMENSIONAL VERTICAL VELOCITY PROFILE

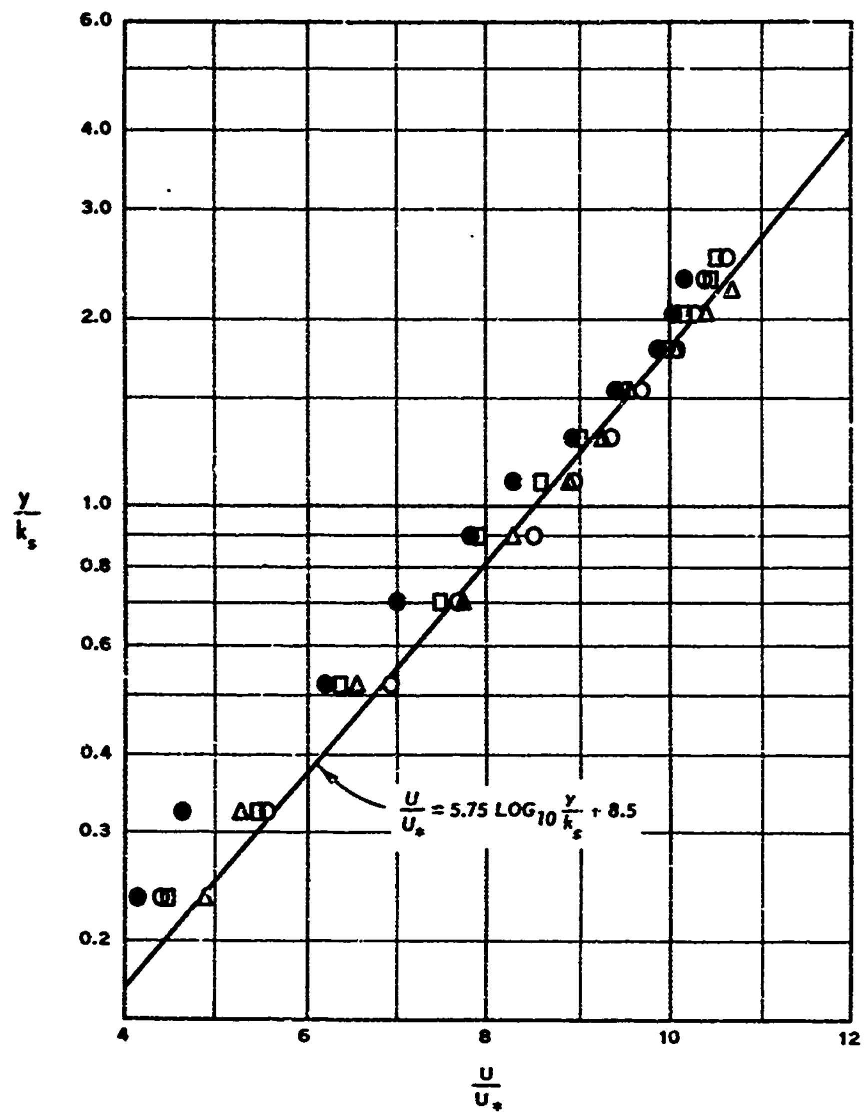
3/4-INCH STONE



LEGEND

	Q, CFS	SLOPE	$\bar{U}$, FPS
●	1.50	0.0023	1.50
○	1.75	0.0023	1.63
□	2.00	0.0023	1.69
■	2.00	0.0040	2.02
▲	2.50	0.0040	2.22
△	2.50	0.0060	2.66

NONDIMENSIONAL
VERTICAL VELOCITY PROFILE
1-INCH STONE

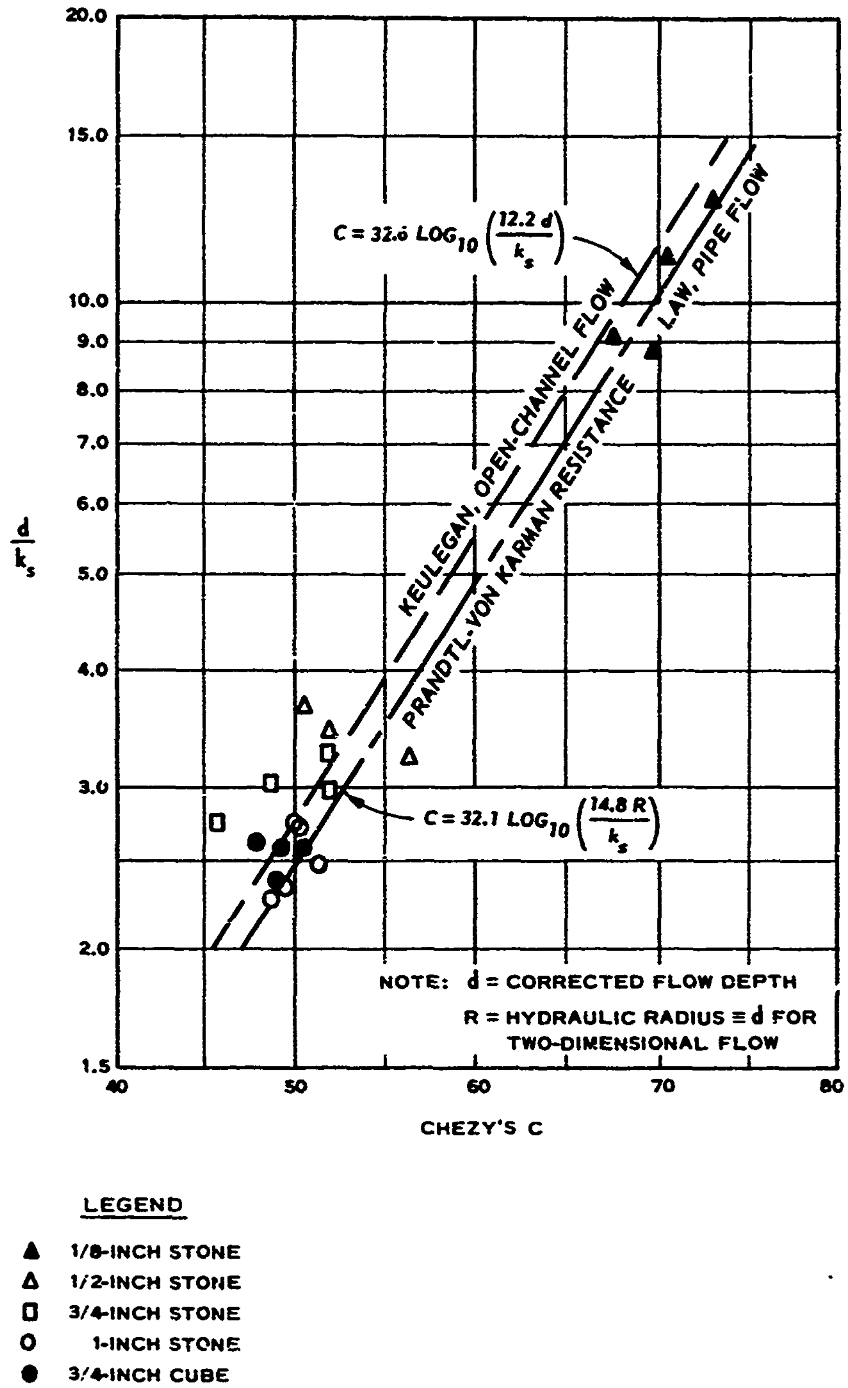


LEGEND

	Q, CFS	SLOPE	$\bar{U}$, FPS
●	1.50	0.0023	1.459
□	1.75	0.0030	1.707
△	1.75	0.0040	1.877
○	2.00	0.0040	2.026

NONDIMENSIONAL VERTICAL VELOCITY PROFILE

3/4-INCH CUBES



RESISTANCE COEFFICIENTS

APPENDIX A: TEST DATA

Table A1

Experimental Data, 1/8-in. Stone

Distance from Top of Roughness h , ft	Velocity U , fps	Surface Profile	
		Station	Depth of Flow d , ft
Q = 0.75 cfs, Slope = 0.0023, Water Temperature = 67 F			
0.005	0.86	0+19	0.223
0.020	1.11	0+21	0.220
0.030	1.24	0+23	0.219
0.040	1.33	0+25	0.218
0.050	1.37	0+27	0.218
0.060	1.41	0+29	0.216
0.080	1.51	0+31	0.216
0.100	1.59	0+33	0.218
0.120	1.63	0+35	0.217
0.140	1.66	0+37	0.217
0.160	1.71	0+38.5	0.217
0.180	1.73	0+43	0.215
0.196	1.75		
Q = 1.50 cfs, Slope = 0.0023, Water Temperature = 68 F			
0.005	1.03	0+22	0.307
0.020	1.32	0+24	0.310
0.040	1.58	0+26	0.307
0.060	1.76	0+28	0.307
0.080	1.78	0+30	0.309
0.100	1.88	0+32	0.308
0.120	1.94	0+34	0.305
0.150	1.99	0+36	0.307
0.180	2.09	0+38	0.305
0.220	2.15	0+42	0.304
0.260	2.20		
0.290	2.25		
Q = 1.25 cfs, Slope = 0.0030 Water Temperature = 70 F			
0.005	1.06	0+21	0.267
0.020	1.40	0+23	0.269
0.030	1.50	0+25	0.267
0.040	1.58	0+27	0.270
0.050	1.66	0+29	0.266
0.060	1.72	0+31	0.268
0.070	1.76		
0.080	1.81	0+33	0.266
0.100	1.89	0+34	0.264
0.120	1.95	0+35	0.264
0.150	2.02	0+36	0.265
0.180	2.08	0+37	0.267
0.210	2.12	0+38	0.267
0.240	2.12	0+42	0.264
Q = 1.00 cfs, Slope = 0.0040, Water Temperature = 64 F			
0.005	1.15	0+21	0.218
0.020	1.46	0+23	0.214
0.030	1.66	0+25	0.213
0.040	1.74	0+27	0.210
0.050	1.85	0+29	0.211
0.060	1.91	0+31	0.211
0.070	2.01	0+33	0.215
0.090	2.11	0+34	0.208
0.100	2.13	0+35	0.212
0.110	2.16	0+36	0.214
0.120	2.20	0+37	0.210
0.140	2.24	0+38	0.208
0.160	2.26	0+43	0.206
0.180	2.32		

Table A2

Experimental Data, 1/2-in. Stone

Distance from Top of Roughness h , ft	Velocity U , fps	Surface Profile Station	Surface Profile Depth of Flow d , ft
Q = 1.25 cfs, Slope = 0.0023, Water Temperature = 83 F			
0.020	0.90	0+22	0.330
0.050	1.09	0+24	0.330
0.080	1.28	0+26	0.326
0.110	1.38	0+28	0.325
0.140	1.47	0+30	0.323
0.170	1.58	0+32	0.325
0.200	1.63	0+34	0.326
0.230	1.67	0+36	0.324
0.260	1.73	0+38	0.324
0.290	1.77	0+41	0.323
0.310	1.81	0+43	0.322
		0+45	0.320
Q = 1.75 cfs, Slope = 0.0023, Water Temperature = 85 F			
0.020	0.96	0+22	0.429
0.050	1.22	0+24	0.429
0.080	1.33	0+26	0.429
0.110	1.45	0+28	0.428
0.140	1.52	0+30	0.428
0.170	1.61	0+32	0.429
0.200	1.64	0+34	0.431
0.240	1.69	0+36	0.430
0.280	1.75	0+38	0.430
0.320	1.82	0+41	0.431
0.360	1.87	0+43	0.429
0.400	1.94	0+45	0.429
Q = 1.75 cfs, Slope = 0.0040, Water Temperature = 85 F			
0.016	1.40	0+22	0.343
0.030	1.46	0+24	0.346
0.060	1.64	0+26	0.344
0.090	1.78	0+28	0.342
0.120	1.89	0+30	0.339
0.150	1.99	0+32	0.342
0.180	2.07	0+34	0.346
0.210	2.16	0+36	0.345
0.240	2.26	0+38	0.344
0.270	2.33	0+41	0.346
0.300	2.38	0+43	0.343
0.330	2.38	0+45	0.343
Q = 2.00 cfs, Slope = 0.0060, Water Temperature = 68 F			
0.030	1.77	0+22	0.310
0.060	2.03	0+24	0.308
0.090	2.25	0+26	0.300
0.120	2.41	0+28	0.301
0.150	2.54	0+30	0.299
0.180	2.64	0+32	0.303
0.210	2.74	0+34	0.310
0.240	2.79	0+36	0.300
0.270	2.86	0+38	0.300
		0+41	0.293
		0+43	0.397
		0+45	0.395

Table A3

Experimental Data, 3/4-in. Stone

Distance from Top of Roughness h, ft	Velocity U, fps	Surface Profile Station	Surface Profile Depth of Flow d, ft
Q = 1.00 cfs, Slope = 0.0023, Water Temperature = 78 F			
0.015	0.88	0+22	0.324
0.020	0.92	0+24	0.324
0.030	0.99	0+26	0.323
0.040	1.01	0+28	0.324
0.050	1.05	0+30	0.325
0.060	1.08	0+32	0.324
0.070	1.10	0+34	0.322
0.080	1.14	0+36	0.323
0.100	1.20	0+38	0.323
0.120	1.28	0+40	0.323
0.140	1.32	0+42	0.322
0.160	1.35	0+44	0.329
0.180	1.39		
0.200	1.42		
0.220	1.44		
0.250	1.49		
0.280	1.53		
0.305	1.55		
Q = 1.50 cfs, Slope = 0.0023, Water Temperature = 76 F			
0.020	1.04	0+22	0.384
0.040	1.16	0+24	0.381
0.060	1.30	0+26	0.381
0.080	1.44	0+28	0.379
0.100	1.47	0+30	0.378
0.120	1.54	0+32	0.378
0.150	1.61	0+34	0.378
0.180	1.70	0+36	0.377
0.210	1.73	0+38	0.376
0.240	1.80	0+41	0.375
0.270	1.84	0+43	0.377
0.300	1.86	0+45	0.369
0.330	1.90		
0.360	1.93		
Q = 1.75 cfs, Slope = 0.0040, Water Temperature = 73 F			
0.010	1.19	0+22	0.358
0.020	1.34	0+24	0.351
0.030	1.45	0+26	0.358
0.040	1.53	0+28	0.356
0.050	1.58	0+30	0.350
0.060	1.67	0+32	0.351
0.080	1.70	0+34	0.360
0.100	1.84	0+36	0.352
0.120	1.95	0+38	0.352
0.150	2.07	0+41	0.350
0.180	2.12	0+43	0.355
0.210	2.20	0+45	0.337
0.240	2.27		
0.270	2.34		
0.300	2.38		
0.330	2.41		
Q = 2.00 cfs, Slope = 0.0060, Water Temperature = 76 F			
0.020	1.40	0+22	0.366
0.030	1.55	0+24	0.379
0.040	1.67	0+26	0.376
0.060	1.86	0+28	0.366
0.080	2.05	0+30	0.382
0.100	2.13	0+32	0.374
0.120	2.21	0+34	0.367
0.150	2.34	0+36	0.366
0.180	2.46	0+38	0.360
.210	2.52	0+41	0.362
[illegible]40	2.62	0+43	0.356
[illegible]70	2.[illegible]7		

Table A4

Experimental Data, 1-in. Stone

Distance from Top of Roughness h, ft	Velocity U, fps	Surface Profile Station	Depth of Flow d, ft
Q = 1.50 cfs, Slope = 0.0023, Water Temperature = 74 F			
0.016	0.94	0+21	0.379
0.036	1.00	0+23	0.382
0.066	1.15	0+25	0.379
0.096	1.25	0+27	0.379
0.146	1.41	0+29	0.379
0.196	1.54	0+31	0.380
0.246	1.66	0+33	0.380
0.296	1.79	0+35	0.380
0.346	1.83	0+37	0.380
		0+41	0.380
		0+43	0.380
		0+45	0.381
Q = 1.75 cfs, Slope = 0.0023, Water Temperature = 72 F			
0.016	1.00	0+21	0.418
0.036	1.13	0+23	0.420
0.066	1.29	0+25	0.417
0.096	1.36	0+27	0.418
0.146	1.54	0+29	0.419
0.196	1.67	0+31	0.418
0.246	1.78	0+33	0.417
0.296	1.87	0+35	0.418
0.346	1.98	0+37	0.417
0.396	2.01	0+41	0.415
		0+43	0.415
		0+45	0.415
Q = 2.00 cfs, Slope = 0.0023, Water Temperature = 74 F			
0.016	1.00	0+21	0.466
0.036	1.19	0+23	0.470
0.066	1.31	0+25	0.468
0.096	1.40	0+27	0.470
0.146	1.57	0+29	0.470
0.196	1.73	0+31	0.470
0.246	1.82	0+33	0.472
0.296	1.87	0+35	0.470
0.346	1.92	0+37	0.470
0.396	1.98	0+41	0.469
0.446	1.98	0+43	0.470
		0+45	0.469
Q = 2.00 cfs, Slope = 0.0040, Water Temperature = 76 F			
0.016	1.21	0+21	0.384
0.036	1.43	0+23	0.390
0.066	1.66	0+25	0.389
0.096	1.75	0+27	0.392
0.146	1.94	0+29	0.393
0.196	2.11	0+31	0.390
0.246	2.25	0+33	0.390
0.296	2.36	0+35	0.387
0.346	2.39	0+37	0.386
		0+38.5	0.390
		0+41	0.388
		0+43	0.389
		0+45	0.385
Q = 2.50 cfs, Slope = 0.0040, Water Temperature = 77 F			
0.016	1.38	0+22	0.465
0.036	1.53	0+24	0.463
0.066	1.70	0+26	0.463
0.096	1.81	0+28	0.463
0.146	2.06	0+30	0.465
0.196	2.23	0+32	[illegible]
0.246	2.33	0+34	0.464
0.296	2.44	0+36	0.464
0.346	2.53	0+38	0.466
0.396	2.61	0+41	[illegible]
		0+43	[illegible]
		0+45	[illegible]
Q = 2.50 cfs, Slope = 0.0060, Water Temperature = 78 F			
0.016	1.68	0+22	0.406
0.036	1.84	0+24	0.411
0.066	2.06	0+26	[illegible]
0.096	2.14	0+28	0.407
0.146	2.45	[illegible]	0.409
0.196	2.88	[illegible]	0.410
0.246	2.98	0+34	0.406
0.296	3.06	0+36	0.414
0.346	3.14	0+38	0.419
		0+41	0.410
		0+43	0.414
		0+45	0.410

Table A5

Experimental Data, 3/4-in. Concrete Cubes

Distance from Top of Roughness h, ft	Velocity U, fps	Surface Profile Station	Surface Profile Depth of Flow d, ft
Q = 1.50 cfs, Slope = 0.0023, Water Temperature = 85 F			
0.016	0.72	0+19	0.385
0.030	0.81	0+21	0.382
0.060	1.08	0+22	0.383
0.090	1.22	0+23	0.384
0.120	1.36	0+24	0.383
0.150	1.44	0+25	0.384
0.180	1.55	0+26	0.384
0.220	1.63	0+27	0.383
0.260	1.71	0+28	0.383
0.300	1.74	0+29	0.382
0.340	1.76	0+30	0.380
		0+31	0.382
Q = 1.75 cfs, Slope = 0.0030, Water Temperature = 87 F			
0.016	0.88	0+19	0.382
0.030	1.08	0+22	0.380
0.060	1.26	0+23	0.382
0.090	1.48	0+24	0.382
0.120	1.56	0+25	0.382
0.150	1.70	0+26	0.382
0.180	1.77	0+27	0.382
0.220	1.86	0+28	0.381
0.260	1.94	0+29	0.382
0.300	2.00	0+30	0.380
0.340	2.06		
0.370	2.06		
Q = 1.75 cfs, Slope = 0.0040, Water Temperature = 86 F			
0.016	1.06	0+19	0.349
0.030	1.16	0+22	0.349
0.060	1.43	0+23	0.351
0.090	1.68	0+24	0.349
0.120	1.80	0+25	0.348
0.150	1.94	0+26	0.348
0.180	2.02	0+27	0.347
0.220	2.09	0+28	0.346
0.260	2.19	0+29	0.347
0.300	2.28	0+30	0.345
0.330	2.33		
Q = 2.00 cfs, Slope = 0.0040, Water Temperature = 75 F			
0.016	1.00	0+18	0.385
0.030	1.27	0+19	0.382
0.060	1.58	0+20	0.382
0.090	1.75	0+21	0.380
0.120	1.94	0+22	0.382
0.150	2.03	0+23	0.384
0.180	2.13	0+24	0.384
0.220	2.20	0+25	0.384
0.260	2.30	0+26	0.384
0.300	2.34	0+27	0.384
0.340	2.38	0+28	0.382
0.370	2.42	0+29	0.384
		0+30	0.381
		0+31	0.381

Table A6

Experimental Data, 1/8-in. Stone

Boundary Roughness Point Gage Readings (10^{-4} in.)

345.00	379.00	1533.00	546.00	77.00	1074.00	1326.00	726.00	954.00	763.00	1272.00
1017.00	786.00	1007.00	806.00	1100.00	1148.00	20.00	2066.00	1386.00	1085.00	1726.00
1167.00	887.00	778.00	1437.00	1318.00	1301.00	1266.00	1474.00	532.00	1291.00	1507.00
1510.00	1166.00	1199.00	626.00	768.00	731.00	1327.00	854.00	823.00	808.00	645.00
837.00	1539.00	839.00	1514.00	1426.00	1347.00	871.00	1301.00	1309.00	1022.00	1330.00
1316.00	986.00	1634.00	2189.00	1249.00	1453.00	629.00	1286.00	1024.00	635.00	1013.00
771.00	1160.00	1469.00	951.00	786.00	1415.00	1037.00	1859.00	1285.00	1236.00	1466.00
1235.00	1584.00	1202.00	855.00	1060.00	908.00	1466.00	1538.00	1605.00	1771.00	1041.00
1356.00	1456.00	1468.00	682.00	869.00	1104.00	556.00	1307.00	585.00	506.00	671.00
1833.00	668.00	15.00	837.00	747.00	1367.00	1102.00	1105.00	1909.00	808.00	858.00
1303.00	662.00	1070.00	1087.00	1086.00	1104.00	730.00	837.00	468.00	736.00	41.00
1076.00	1515.00	1124.00	1031.00	1896.00	2094.00	2106.00	1837.00	1168.00	1376.00	1122.00
825.00	1149.00	2007.00	1457.00	1905.00	1920.00	1735.00	1577.00	1901.00	1437.00	544.00
1536.00	379.00	1173.00	1342.00	663.00	544.00	708.00	879.00	1311.00	974.00	769.00
1146.00	719.00	1336.00	1207.00	523.00	1266.00	1318.00	1367.00	1337.00	970.00	1866.00
1806.00	1828.00	2097.00	1586.00	1383.00	439.00	546.00	1446.00	892.00	1566.00	942.00
1396.00	1392.00	539.00	1574.00	875.00	1258.00	826.00	1535.00	918.00	771.00	200.00
845.00	1311.00	1368.00	1376.00	1445.00	1141.00	2024.00	1957.00	1348.00	346.00	666.00
886.00	1495.00	985.00	916.00	717.00	1506.00	1008.00	1722.00	1832.00	779.00	1338.00
1312.00	653.00	941.00	1177.00	1566.00	1285.00	1062.00	817.00	1002.00	938.00	1128.00
1394.00	1611.00	1038.00	1406.00	1473.00	996.00	1777.00	1074.00	524.00	927.00	1104.00
765.00	1595.00	1393.00	904.00	1575.00	1421.00	949.00	1375.00	239.00	797.00	856.00
1575.00	1398.00	1538.00	1298.00	1125.00	489.00	1147.00	1046.00	128.00	1362.00	871.00
1013.00	584.00	341.00	616.00	1172.00	581.00	1225.00	1727.00	1067.00	1549.00	781.00
1385.00	975.00	337.00	901.00	587.00	1236.00	1468.00	1095.00	1825.00	1143.00	1115.00
1038.00	612.00	1426.00	1291.00	641.00	1110.00	707.00	1486.00	1016.00	1747.00	1178.00
650.00	1727.00	1486.00	293.00	848.00	314.00	958.00	844.00	1292.00	767.00	1357.00
598.00	1212.00	1416.00	802.00	626.00	536.00	875.00	1369.00	1201.00	1210.00	1302.00
1325.00	1064.00	633.00	708.00	201.00	1346.00	975.00	1333.00	1195.00	1354.00	1348.00
936.00	1185.00	1255.00	777.00	350.00	1527.00	1090.00	1596.00	861.00	1326.00	1565.00
1014.00	577.00	816.00	771.00	634.00	890.00	1231.00	865.00	376.00	1141.00	979.00
928.00	276.00	1119.00	1394.00	1156.00	1639.00	564.00	1378.00	1348.00	1446.00	246.00
1012.00	836.00	559.00	551.00	221.00	848.00	1297.00	965.00	1092.00	1496.00	1095.00
1178.00	481.00	781.00	779.00	1171.00	355.00	957.00	701.00	770.00	97.00	1178.00
836.00	975.00	552.00	1365.00	1071.00	909.00	797.00	943.00	672.00	1263.00	753.00
670.00	487.00	985.00	585.00	325.00	993.00	1155.00	1190.00	891.00	1256.00	686.00
541.00	1555.00	692.00	781.00	235.00	901.00	992.00	0.00	408.00	795.00	1653.00
1326.00	1340.00	874.00	666.00	1040.00	757.00	951.00	905.00	703.00	1031.00	1408.00
892.00	475.00	1349.00	302.00	972.00	1813.00	860.00	9.00	573.00	1023.00	874.00
1073.00	709.00	956.00	506.00	402.00	802.00	1416.00	1161.00	822.00	657.00	449.00
1571.00	1132.00	744.00	968.00	667.00	350.00	1306.00	324.00	1226.00	969.00	1556.00
1259.00	1201.00	839.00	966.00	373.00	602.00	935.00	1239.00	977.00	1474.00	1530.00
984.00	1376.00	1221.00	1697.00	1517.00	909.00	851.00	964.00	843.00	1488.00	1337.00
1288.00	652.00	323.00	1399.00	536.00	339.00	1339.00	626.00	577.00	1266.00	1429.00
626.00	475.00	756.00	839.00	1559.00	722.00	1478.00	912.00	1253.00	1596.00	861.00
1092.00	766.00	768.00	1479.00	895.00	1702.00	1544.00	1233.00	941.00	658.00	698.00
981.00	1132.00	1622.00	1605.00	1637.00	917.00	1477.00	738.00	647.00	1214.00	571.00
589.00	1043.00	1186.00	1450.00	1456.00	1146.00	1608.00	1407.00	1121.00	2098.00	1277.00
502.00	878.00	1434.00	1075.00	1116.00	1784.00	56.00	996.00	1366.00	1353.00	580.00
1569.00	1182.00	1102.00	819.00	928.00	1209.00	17.00	805.00	751.00	1035.00	1208.00
1700.00	1011.00	869.00	1336.00	846.00	836.00	1195.00	1826.00	1506.00	1100.00	1257.00
894.00	1817.00	1608.00	717.00	250.00	1073.00	924.00	1384.00	1270.00	1008.00	1403.00
695.00	1346.00	896.00	669.00	1756.00	1446.00	1619.00	1562.00	892.00	386.00	1073.00
1389.00	586.00	1236.00	1580.00	1925.00	2095.00	946.00	1160.00	1421.00	1637.00	2068.00
1644.00	1625.00	1536.00	1090.00	847.00	1004.00	1469.00	1051.00	1687.00	1091.00	776.00
2091.00	2031.00	2092.00	1461.00	1459.00	916.00	1017.00	1780.00	1477.00	708.00	1167.00
1511.00	1149.00	947.00	1318.00	1372.00	1450.00	1426.00	1243.00	912.00	1590.00	1882.00
1433.00	1040.00	1090.00	1524.00	848.00	1704.00	1194.00	1026.00	2098.00	1549.00	600.00
576.00	1177.00	1496.00	1153.00	1207.00	1047.00	1732.00	981.00	1826.00	1306.00	1190.00
792.00	341.00	693.00	1136.00	938.00	1081.00	465.00	1083.00	1536.00	1616.00	972.00
1027.00	1383.00	1369.00	1580.00	1995.00	1749.00	1150.00	1295.00	1504.00	967.00	948.00
28.00	349.00	604.00	1041.00	1366.00	1246.00	1200.00	1622.00	267.00	1350.00	169.00
151.00	839.00	406.00	1016.00	878.00	1380.00	1016.00	1227.00	663.00	493.00	1492.00
1661.00	770.00	842.00	1030.00	1515.00	1554.00	1367.00	924.00	1066.00	1166.00	686.00
854.00	877.00	1486.00	1197.00	1436.00	708.00	2096.00	527.00	786.00	1679.00	1386.00
1877.00	2095.00	1954.00	1833.00	982.00	669.00	1043.00	1541.00	1172.00	527.00	838.00
1353.00	1287.00	1527.00	1185.00	1077.00	1412.00	1227.00	296.00	2096.00	1685.00	1003.00
1004.00	882.00	1068.00	1166.00	983.00	1656.00	935.00	1972.00	1569.00	1336.00	648.00
692.00	672.00	1156.00	1640.00	821.00	1521.00	1297.00	1492.00	218.00	1039.00	1454.00
1300.00	1180.00	1285.00	1447.00	1430.00	1136.00	1840.00	2071.00	1719.00	1109.00	1139.00
1240.00	936.00	1020.00	965.00	899.00	1079.00	1658.00	639.00	990.00	575.00	1058.00
1439.00	1197.00	1375.00	1795.00	1529.00	1516.00	1462.00	968.00	1330.00	1137.00	367.00
2084.00	1261.00	1781.00	1072.00	1277.00	2095.00	1038.00	570.00	1474.00	1194.00	735.00
1328.00	794.00	1572.00	1606.00	1536.00	775.00	644.00	729.00	286.00	889.00	1419.00
970.00	767.00	1703.00	1023.00	1047.00	570.00	1266.00	869.00	826.00	77.00	15.00
474.00	853.00	1381.00	966.00	468.00	1026.00	772.00	666.00	174.00	1426.00	1218.00
1281.00	1258.00	1408.00	1200.00	432.00	1354.00	1146.00	1067.00	876.00	986.00	1251.00
1309.00	1522.00	2057.00	985.00	456.00	806.00	1276.00	946.00	1224.00	1087.00	1854.00
1718.00	1143.00	2056.00	1678.00	714.00	1300.00	1251.00	1040.00	1560.00	1717.00	1430.00
2100.00	1729.00	1922.00	1389.00	1093.00	1535.00	1179.00	1097.00	1595.00	1267.00	1246.00
1024.00	601.00	629.00	1021.00	16.00	1201.00	1029.00	1926.00	1507.00	1803.00	442.00
426.00	989.00	1338.00	176.00	1705.00	1946.00	2100.00	1366.00	1469.00		

Table A7

Experimental Data, 1/2-in. Stone

Boundary Roughness Point Gage Readings (10^{-3} ft)

266.00	257.00	259.00	240.00	279.00	248.00	240.00	240.00	244.00	267.00	268.00
260.00	271.00	240.00	288.00	279.00	240.00	263.00	263.00	262.00	261.00	263.00
271.00	288.00	267.00	288.00	283.00	247.00	260.00	262.00	240.00	265.00	261.00
268.00	287.00	277.00	282.00	250.00	249.00	250.00	241.00	248.00	[illegible]	248.00
282.00	280.00	280.00	279.00	267.00	260.00	249.00	243.00	265.00	243.00	240.00
287.00	250.00	243.00	272.00	271.00	243.00	251.00	262.00	258.00	247.00	279.00
279.00	262.00	265.00	263.00	254.00	252.00	263.00	257.00	245.00	240.00	265.00
246.00	283.00	282.00	276.00	267.00	271.00	273.00	286.00	277.00	246.00	250.00
248.00	276.00	274.00	269.00	262.00	270.00	286.00	263.00	282.00	240.00	250.00
257.00	287.00	272.00	270.00	264.00	269.00	274.00	273.00	270.00	250.00	263.00
258.00	[illegible]	264.00	283.00	272.00	267.00	268.00	230.00	257.00	255.00	282.00
240.00	264.00	257.00	257.00	267.00	263.00	252.00	243.00	268.00	248.00	240.00
274.00	247.00	242.00	240.00	259.00	263.00	240.00	253.00	266.00	263.00	240.00
258.00	240.00	250.00	249.00	243.00	259.00	240.00	263.00	265.00	268.00	240.00
260.00	266.00	257.00	246.00	269.00	240.00	253.00	263.00	265.00	271.00	240.00
274.00	249.00	271.00	242.00	251.00	269.00	268.00	259.00	256.00	265.00	248.00
232.00	261.00	240.00	257.00	245.00	270.00	267.00	260.00	256.00	263.00	272.00
240.00	262.00	263.00	266.00	272.00	275.00	262.00	244.00	263.00	271.00	268.00
240.00	263.00	262.00	267.00	250.00	268.00	254.00	265.00	240.00	263.00	261.00
240.00	240.00	270.00	259.00	259.00	277.00	279.00	261.00	261.00	250.00	253.00
274.00	268.00	263.00	243.00	242.00	256.00	255.00	252.00	250.00	262.00	264.00
276.00	240.00	268.00	257.00	272.00	274.00	275.00	267.00	260.00	240.00	262.00
252.00	263.00	274.00	279.00	248.00	260.00	272.00	274.00	272.00	260.00	262.00
265.00	238.00	248.00	259.00	242.00	240.00	259.00	273.00	241.00	244.00	250.00
259.00	260.00	253.00	260.00	258.00	262.00	273.00	263.00	261.00	240.00	250.00
267.00	250.00	253.00	257.00	250.00	261.00	265.00	260.00	273.00	240.00	259.00
255.00	249.00	277.00	272.00	262.00	282.00	253.00	266.00	270.00	264.00	254.00
247.00	260.00	258.00	258.00	264.00	279.00	267.00	240.00	240.00	263.00	245.00
272.00	263.00	262.00	255.00	240.00	263.00	265.00	258.00	245.00	243.00	268.00
267.00	270.00	271.00	261.00	275.00	252.00	240.00	240.00	253.00	249.00	264.00
263.00	262.00	253.00	243.00	277.00	269.00	240.00	240.00	252.00	263.00	272.00
249.00	240.00	263.00	240.00	269.00	280.00	259.00	240.00	240.00	244.00	257.00
240.00	260.00	240.00	240.00	256.00	268.00	275.00	240.00	250.00	245.00	250.00
260.00	266.00	269.00	281.00	263.00	265.00	275.00	263.00	288.00	266.00	257.00
297.00	286.00	262.00	260.00	254.00	273.00	245.00	247.00	256.00	274.00	273.00
296.00	286.00	253.00	242.00	252.00	249.00	244.00	258.00	286.00	264.00	252.00
258.00	268.00	252.00	252.00	250.00	253.00	261.00	272.00	244.00	257.00	255.00
289.00	284.00	247.00	241.00	240.00	262.00	279.00	267.00	283.00	252.00	244.00
289.00	288.00	287.00	268.00	267.00	260.00	259.00	262.00	287.00	245.00	252.00
293.00	287.00	287.00	256.00	262.00	277.00	282.00	266.00	267.00	272.00	259.00
278.00	291.00	279.00	278.00	263.00	278.00	279.00	270.00	278.00	262.00	240.00
270.00	256.00	257.00	267.00	258.00	262.00	242.00	258.00	279.00	240.00	282.00
256.00	258.00	240.00	276.00	243.00	240.00	252.00	278.00	244.00	279.00	275.00
265.00	240.00	257.00	255.00	293.00	293.00	272.00	285.00	240.00	259.00	273.00
243.00	277.00	267.00	263.00	285.00	277.00	281.00	280.00	280.00	273.00	282.00
279.00	293.00	292.00	289.00	293.00	293.00	275.00	284.00	287.00	290.00	292.00
286.00	273.00	296.00	262.00	294.00	295.00	245.00	288.00	290.00	279.00	288.00
273.00	266.00	265.00	255.00	242.00	246.00	252.00	258.00	279.00	281.00	257.00
277.00	276.00	288.00	295.00	267.00	254.00	279.00	281.00	283.00	284.00	267.00
258.00	260.00	273.00	287.00	285.00	270.00	283.00	276.00	260.00	260.00	278.00
248.00	284.00	287.00	282.00	269.00	278.00	274.00	278.00	292.00	289.00	283.00
279.00	278.00	286.00	294.00	287.00	278.00	283.00	263.00	290.00	279.00	253.00
271.00	282.00	289.00	273.00	263.00	272.00	267.00	293.00	293.00	283.00	264.00
240.00	282.00	281.00	277.00	274.00	290.00	256.00	278.00	273.00	279.00	278.00
241.00	282.00	278.00	282.00	278.00	293.00	266.00	253.00	283.00	280.00	207.00
288.00	288.00	287.00	282.00	266.00	267.00	267.00	267.00	262.00	288.00	279.00
279.00	279.00	260.00	280.00	262.00	262.00	263.00	277.00	279.00	27 00	256.00
259.00	261.00	260.00	259.00	265.00	257.00	263.00	287.00	279.00	26	270.00
263.00	278.00	264.00	277.00	[illegible]	248.00	247.00	283.00	283.00	266	264.00
278.00	278.00	270.00	275.00	272.00	264.00	267.00	273.00	262.00	263.00	262.00
252.00	279.00	284.00	274.00	287.00	266.00	263.00	269.00	281.00	282.00	281.00
270.00	280.00	284.00	293.00	292.00	283.00	248.00	268.00	275.00	279.00	267.00
261.00	267.00	262.00	250.00	250.00	255.00	271.00	269.00	286.00	273.00	262.00
254.00	240.00	264.00	255.00	252.00	259.00	267.00	247.00	274.00	262.00	248.00
258.00	265.00	257.00	254.00	242.00	279.00	247.00	253.00	279.00	247.00	274.00
260.00	263.00	268.00	258.00	255.00	267.00	279.00	250.00	240.00	269.00	251.00
287.00	253.00	254.00	275.00	278.00	286.00	283.00	267.00	276.00	268.00	278.00
280.00	259.00	261.00	283.00	262.00	256.00	287.00	285.00	278.00	266.00	261.00
275.00	257.00	253.00	255.00	279.00	285.00	287.00	254.00	256.00	278.00	276.00
285.00	281.00	261.00	250.00	240.00	284.00	273.00	273.00	273.00	283.00	273.00
287.00	289.00	260.00	263.00	248.00	279.00	273.00	281.00	282.00	273.00	269.00
285.00	290.00	285.00	257.00	267.00	270.00	278.00	283.00	285.00	273.00	263.00
287.00	285.00	287.00	262.00	253.00	279.00	285.00	276.00	288.00	273.00	265.00
283.00	283.00	287.00	204.00	263.00	267.00	282.00	286.00	270.00	245.00	269.00

Table A8

Experimental Data, 3/4-in. Stone

Boundary Roughness Point Gage Readings (10^{-3} ft)

317.00	325.00	319.00	302.00	305.00	353.00	329.00	343.00	341.00	346.00	348.00
338.00	334.00	318.00	337.00	330.00	318.00	334.00	341.00	336.00	331.00	304.00
304.00	347.00	347.00	308.00	291.00	294.00	331.00	350.00	352.00	346.00	320.00
323.00	306.00	331.00	315.00	290.00	323.00	346.00	341.00	346.00	354.00	339.00
337.00	337.00	324.00	335.00	329.00	315.00	334.00	339.00	343.00	336.00	325.00
327.00	326.00	318.00	350.00	302.00	304.00	321.00	342.00	346.00	335.00	332.00
337.00	334.00	319.00	319.00	301.00	331.00	311.00	305.00	333.00	345.00	346.00
321.00	295.00	317.00	339.00	326.00	341.00	320.00	330.00	326.00	323.00	322.00
331.00	340.00	301.00	292.00	318.00	336.00	315.00	287.00	312.00	318.00	328.00
340.00	339.00	333.00	311.00	340.00	351.00	336.00	341.00	347.00	305.00	340.00
334.00	321.00	310.00	320.00	335.00	329.00	305.00	291.00	311.00	288.00	317.00
332.00	327.00	298.00	315.00	335.00	334.00	310.00	301.00	330.00	314.00	320.00
338.00	337.00	328.00	309.00	340.00	343.00	306.00	340.00	344.00	345.00	340.00
329.00	313.00	306.00	320.00	333.00	324.00	309.00	292.00	314.00	287.00	317.00
332.00	325.00	294.00	304.00	332.00	338.00	307.00	328.00	326.00	321.00	331.00
326.00	320.00	343.00	327.00	332.00	340.00	324.00	336.00	326.00	314.00	324.00
334.00	321.00	312.00	328.00	316.00	302.00	322.00	328.00	319.00	276.00	304.00
346.00	338.00	335.00	321.00	328.00	329.00	322.00	312.00	305.00	319.00	303.00
310.00	311.00	335.00	337.00	326.00	332.00	334.00	332.00	327.00	314.00	303.00
331.00	325.00	316.00	335.00	337.00	323.00	332.00	297.00	345.00	351.00	345.00
338.00	290.00	343.00	341.00	331.00	340.00	345.00	317.00	323.00	340.00	339.00
338.00	326.00	333.00	336.00	333.00	340.00	339.00	333.00	332.00	322.00	331.00
348.00	319.00	317.00	310.00	319.00	310.00	325.00	339.00	336.00	321.00	322.00
283.00	323.00	342.00	339.00	330.00	314.00	320.00	337.00	329.00	[illegible]	312.00
279.00	320.00	344.00	340.00	318.00	339.00	336.00	339.00	333.00	[illegible]	347.00
296.00	320.00	329.00	335.00	296.00	295.00	308.00	320.00	317.00	[illegible]	345.00
326.00	324.00	332.00	333.00	334.00	336.00	334.00	331.00	340.00	329.00	291.00
340.00	325.00	330.00	336.00	344.00	345.00	296.00	310.00	326.00	320.00	307.00
272.00	328.00	335.00	339.00	333.00	315.00	292.00	318.00	321.00	297.00	316.00
301.00	326.00	345.00	334.00	292.00	329.00	339.00	335.00	338.00	343.00	348.00
283.00	329.00	328.00	334.00	321.00	315.00	306.00	316.00	334.00	345.00	335.00
283.00	330.00	342.00	340.00	334.00	323.00	297.00	316.00	301.00	250.00	337.00
351.00	329.00	333.00	344.00	332.00	325.00	329.00	328.00	325.00	325.00	291.00
325.00	311.00	354.00	307.00	319.00	347.00	348.00	340.00	337.00	335.00	350.00
344.00	330.00	333.00	344.00	348.00	328.00	302.00	326.00	302.00	308.00	298.00
353.00	348.00	323.00	319.00	300.00	311.00	310.00	305.00	334.00	342.00	346.00
347.00	347.00	333.00	340.00	315.00	329.00	329.00	310.00	292.00	332.00	336.00
350.00	347.00	322.00	321.00	324.00	333.00	347.00	347.00	316.00	250.00	296.00
354.00	326.00	325.00	327.00	358.00	363.00	329.00	346.00	342.00	330.00	334.00
350.00	297.00	336.00	333.00	342.00	348.00	343.00	310.00	304.00	316.00	318.00
309.00	351.00	352.00	351.00	322.00	301.00	278.00	261.00	249.00	317.00	320.00
331.00	330.00	337.00	315.00	321.00	341.00	317.00	323.00	323.00	320.00	311.00
313.00	324.00	325.00	316.00	303.00	341.00	321.00	297.00	323.00	328.00	319.00
346.00	354.00	363.00	311.00	306.00	336.00	329.00	325.00	250.00	308.00	304.00
306.00	295.00	337.00	348.00	347.00	340.00	343.00	334.00	327.00	307.00	310.00
310.00	344.00	332.00	320.00	297.00	342.00	344.00	339.00	337.00	304.00	308.00
339.00	338.00	328.00	335.00	349.00	320.00	328.00	327.00	302.00	316.00	327.00
317.00	344.00	337.00	336.00	307.00	280.00	302.00	338.00	337.00	320.00	309.00
332.00	336.00	341.00	295.00	286.00	338.00	342.00	337.00	322.00	319.00	344.00
353.00	346.00	345.00	343.00	344.00	328.00	330.00	339.00	331.00	344.00	351.00
322.00	340.00	348.00	339.00	330.00	297.00	327.00	343.00	339.00	345.00	305.00
350.00	350.00	344.00	346.00	322.00	324.00	356.00	344.00	323.00	345.00	313.00
358.00	312.00	314.00	287.00	341.00	345.00	345.00	347.00	347.00	349.00	352.00
315.00	319.00	323.00	312.00	329.00	345.00	340.00	334.00	318.00	345.00	336.00
330.00	337.00	324.00	[illegible]	[illegible]	344.00	325.00	[illegible]	[illegible]	[illegible]	279.00
324.00	[illegible]	[illegible]	346.00	346.00	338.00	336.00	336.00	[illegible]	317.00	337.00
344.00	340.00	355.00	353.00	348.00	337.00	322.00	353.00	355.00	345.00	345.00
344.00	336.00	340.00	348.00	324.00	335.00	328.00	322.00	317.00	335.00	337.00
328.00	337.00	336.00	331.00	316.00	327.00	337.00	343.00	345.00	352.00	343.00
294.00	281.00	327.00	317.00	328.00	296.00	346.00	350.00	358.00	326.00	324.00
311.00	336.00	359.00	360.00	354.00	353.00	327.00	328.00	341.00	298.00	298.00
347.00	354.00	348.00	342.00	325.00	340.00	325.00	331.00	328.00	316.00	304.00
333.00	330.00	317.00	319.00	320.00	335.00	328.00	345.00	350.00	346.00	298.00
324.00	357.00	354.00	355.00	340.00	339.00	344.00	312.00	311.00	292.00	313.00
344.00	328.00	336.00	319.00	314.00	345.00	349.00	328.00	325.00	352.00	345.00
329.00	345.00	328.00	355.00	348.00	322.00	339.00	344.00	344.00	310.00	300.00
336.00	296.00	343.00	336.00	330.00	330.00	319.00	292.00	347.00	345.00	326.00
300.00	312.00	292.00	269.00	262.00	287.00	290.00	313.00	311.00	328.00	325.00
325.00	352.00	344.00	350.00	335.00	309.00	323.00	338.00	320.00	350.00	347.00

Table A9

Experimental Data, 1-in. Stone

Boundary Roughness Point Gage Readings (10^{-3} ft)

345.00	354.00	319.00	332.00	296.00	298.00	335.00	343.00	341.00	343.00	319.00
338.00	344.00	332.00	312.00	273.00	278.00	280.00	325.00	330.00	348.00	320.00
330.00	310.00	295.00	310.00	329.00	327.00	308.00	317.00	331.00	331.00	303.00
276.00	277.00	327.00	[illegible]	343.00	344.00	340.00	317.00	318.00	317.00	290.00
287.00	279.00	342.00	356.00	373.00	372.00	349.00	344.00	327.00	270.00	265.00
293.00	268.00	296.00	290.00	366.00	373.00	365.00	357.00	359.00	278.00	271.00
350.00	285.00	278.00	279.00	368.00	360.00	355.00	347.00	293.00	[illegible]	289.00
354.00	268.00	289.00	280.00	387.00	343.00	340.00	283.00	292.00	295.00	320.00
353.00	288.00	290.00	290.00	280.00	330.00	333.00	322.00	313.00	302.00	290.00
356.00	278.00	287.00	300.00	305.00	317.00	297.00	308.00	290.00	317.00	298.00
289.00	298.00	307.00	277.00	278.00	269.00	273.00	298.00	315.00	303.00	353.00
298.00	296.00	297.00	360.00	359.00	364.00	367.00	361.00	341.00	357.00	353.00
290.00	299.00	307.00	347.00	343.00	348.00	351.00	346.00	342.00	352.00	353.00
333.00	318.00	319.00	302.00	299.00	312.00	301.00	309.00	324.00	283.00	310.00
351.00	340.00	332.00	308.00	329.00	309.00	292.00	343.00	316.00	373.00	316.00
352.00	347.00	337.00	316.00	335.00	318.00	342.00	330.00	300.00	290.00	308.00
350.00	350.00	343.00	295.00	322.00	328.00	318.00	329.00	307.00	307.00	301.00
343.00	343.00	308.00	310.00	312.00	304.00	286.00	327.00	307.00	335.00	341.00
347.00	287.00	296.00	297.00	323.00	354.00	338.00	320.00	310.00	316.00	343.00
305.00	313.00	291.00	274.00	335.00	357.00	360.00	332.00	297.00	332.00	333.00
325.00	323.00	320.00	320.00	322.00	356.00	343.00	313.00	337.00	340.00	335.00
321.00	310.00	291.00	308.00	364.00	367.00	316.00	320.00	322.00	319.00	321.00
340.00	342.00	300.00	363.00	364.00	360.00	360.00	357.00	345.00	334.00	329.00
327.00	334.00	308.00	374.00	372.00	368.00	362.00	355.00	335.00	295.00	318.00
296.00	273.00	375.00	372.00	373.00	369.00	367.00	358.00	337.00	307.00	304.00
308.00	303.00	301.00	325.00	362.00	367.00	366.00	356.00	339.00	322.00	290.00
337.00	332.00	321.00	297.00	319.00	350.00	356.00	353.00	327.00	337.00	308.00
345.00	338.00	330.00	317.00	320.00	328.00	334.00	349.00	314.00	313.00	306.00
345.00	341.00	332.00	325.00	327.00	334.00	340.00	325.00	290.00	300.00	318.00
340.00	333.00	330.00	342.00	332.00	337.00	327.00	306.00	302.00	292.00	276.00
319.00	364.00	375.00	373.00	365.00	300.00	296.00	332.00	313.00	297.00	282.00
370.00	371.00	372.00	363.00	323.00	313.00	314.00	293.00	282.00	289.00	281.00
333.00	343.00	354.00	345.00	327.00	329.00	293.00	327.00	317.00	344.00	364.00
357.00	398.00	367.00	335.00	365.00	365.00	364.00	370.00	364.00	350.00	345.00
292.00	270.00	263.00	262.00	282.00	283.00	268.00	270.00	286.00	292.00	297.00
292.00	291.00	283.00	263.00	282.00	293.00	302.00	265.00	327.00	337.00	342.00
228.00	317.00	300.00	275.00	292.00	311.00	312.00	299.00	322.00	345.00	327.00
340.00	333.00	327.00	297.00	307.00	320.00	323.00	303.00	280.00	265.00	273.00
340.00	329.00	319.00	305.00	275.00	310.00	318.00	297.00	319.00	287.00	274.00
334.00	324.00	312.00	301.00	294.00	265.00	288.00	309.00	315.00	307.00	287.00
320.00	335.00	320.00	290.00	226.00	321.00	316.00	272.00	280.00	281.00	332.00
323.00	342.00	322.00	312.00	331.00	339.00	343.00	315.00	298.00	298.00	357.00
278.00	347.00	330.00	344.00	353.00	351.00	355.00	350.00	325.00	355.00	363.00
285.00	332.00	333.00	343.00	368.00	361.00	365.00	352.00	336.00	354.00	364.00
310.00	260.00	348.00	355.00	350.00	269.00	280.00	321.00	318.00	315.00	306.00
360.00	350.00	348.00	323.00	332.00	333.00	345.00	355.00	344.00	359.00	340.00
364.00	357.00	334.00	335.00	344.00	343.00	291.00	357.00	363.00	337.00	330.00
365.00	348.00	333.00	344.00	353.00	353.00	285.00	283.00	293.00	370.00	343.00
360.00	345.00	338.00	351.00	357.00	355.00	297.00	303.00	302.00	340.00	343.00
367.00	341.00	298.00	357.00	359.00	362.00	298.00	308.00	338.00	333.00	326.00
293.00	285.00	282.00	272.00	294.00	303.00	302.00	333.00	330.00	330.00	307.00
347.00	346.00	297.00	308.00	307.00	288.00	333.00	344.00	346.00	333.00	320.00
350.00	351.00	316.00	315.00	323.00	325.00	310.00	362.00	365.00	358.00	278.00
350.00	353.00	357.00	318.00	316.00	350.00	368.00	380.00	383.00	382.00	322.00
350.00	349.00	348.00	308.00	349.00	345.00	360.00	373.00	373.00	372.00	350.00
345.00	342.00	333.00	[illegible]	345.00	333.00	312.00	335.00	335.00	303.00	332.00
357.00	390.00	334.00	335.00	337.00	330.00	283.00	329.00	328.00	297.00	328.00
357.00	352.00	347.00	331.00	326.00	330.00	267.00	279.00	314.00	300.00	332.00
360.00	353.00	345.00	295.00	303.00	312.00	278.00	277.00	273.00	305.00	332.00
354.00	347.00	345.00	310.00	295.00	294.00	343.00	285.00	283.00	287.00	342.00
342.00	333.00	333.00	300.00	317.00	324.00	323.00	343.00	393.00	289.00	328.00
327.00	323.00	347.00	335.00	319.00	336.00	342.00	328.00	290.00	285.00	336.00
317.00	333.00	347.00	319.00	319.00	300.00	328.00	317.00	297.00	327.00	330.00
330.00	343.00	353.00	345.00	300.00	313.00	318.00	308.00	327.00	332.00	325.00
338.00	347.00	347.00	345.00	290.00	300.00	301.00	303.00	329.00	325.00	321.00
320.00	323.00	330.00	289.00	298.00	295.00	300.00	306.00	324.00	320.00	312.00
290.00	285.00	291.00	318.00	342.00	348.00	303.00	311.00	317.00	309.00	303.00
315.00	284.00	292.00	323.00	343.00	348.00	320.00	340.00	312.00	308.00	307.00
336.00	340.00	288.00	350.00	335.00	329.00	342.00	338.00	305.00	282.00	314.00
343.00	350.00	292.00	312.00	353.00	345.00	348.00	340.00	333.00	283.00	311.00
328.00	314.00	279.00	347.00	352.00	350.00	345.00	341.00	313.00	328.00	320.00
331.00	338.00	343.00	291.00	351.00	359.00	351.00	343.00	327.00	332.00	319.00
323.00	332.00	329.00	315.00	354.00	355.00	353.00	344.00	326.00	369.00	372.00
309.00	321.00	336.00	337.00	357.00	354.00	358.00	348.00	329.00	383.00	367.00
297.00	316.00	318.00	320.00	358.00	357.00	358.00	342.00	323.00	304.00	275.00
288.00	306.00	315.00	341.00	352.00	358.00	357.00	340.00	324.00	305.00	278.00

Table A10

Experimental Data, 3/4-in. Cubes

Boundary Roughness Point Gage Readings (10^{-3} ft)

396.00	488.00	392.00	368.00	363.00	413.00	407.00	380.00	380.00	373.00	343.00
397.00	394.00	389.00	389.00	386.00	382.00	348.00	352.00	368.00	333.00	334.00
377.00	370.00	365.00	383.00	378.00	345.00	360.00	387.00	393.00	380.00	394.00
392.00	389.00	390.00	385.00	360.00	359.00	377.00	357.00	334.00	386.00	390.00
411.00	398.00	382.00	376.00	347.00	357.00	380.00	397.00	373.00	402.00	407.00
410.00	392.00	370.00	358.00	371.00	363.00	388.00	370.00	350.00	371.00	380.00
401.00	357.00	367.00	350.00	371.00	393.00	390.00	333.00	344.00	391.00	380.00
366.00	374.00	363.00	348.00	366.00	393.00	382.00	357.00	360.00	401.00	391.00
372.00	377.00	368.00	387.00	394.00	387.00	357.00	401.00	380.00	363.00	392.00
391.00	483.00	352.00	404.00	405.00	405.00	395.00	402.00	404.00	370.00	343.00
413.00	397.00	373.00	415.00	416.00	409.00	347.00	396.00	400.00	370.00	366.00
363.00	362.00	337.00	403.00	394.00	382.00	417.00	402.00	362.00	380.00	347.00
375.00	339.00	343.00	349.00	340.00	354.00	359.00	391.00	399.00	394.00	386.00
391.00	397.00	356.00	392.00	388.00	391.00	390.00	376.00	365.00	405.00	401.00
347.00	343.00	350.00	352.00	350.00	350.00	371.00	391.00	402.00	372.00	409.00
393.00	380.00	368.00	362.00	379.00	397.00	389.00	367.00	389.00	393.00	360.00
373.00	393.00	378.00	405.00	409.00	412.00	371.00	387.00	392.00	399.00	405.00
345.00	370.00	355.00	339.00	397.00	397.00	394.00	368.00	399.00	408.00	388.00
345.00	343.00	380.00	357.00	383.00	385.00	404.00	397.00	403.00	390.00	380.00
403.00	394.00	398.00	393.00	350.00	406.00	403.00	398.00	375.00	410.00	400.00
350.00	348.00	387.00	387.00	389.00	397.00	391.00	368.00	377.00	413.00	408.00
391.00	380.00	379.00	383.00	381.00	381.00	375.00	389.00	371.00	347.00	346.00
372.00	373.00	399.00	387.00	383.00	346.00	345.00	338.00	407.00	396.00	393.00
343.00	484.00	405.00	399.00	400.00	397.00	395.00	345.00	353.00	373.00	357.00
358.00	404.00	392.00	391.00	388.00	334.00	330.00	397.00	388.00	397.00	375.00
403.00	401.00	396.00	413.00	403.00	397.00	359.00	367.00	376.00	337.00	359.00
391.00	393.00	370.00	407.00	409.00	353.00	381.00	364.00	382.00	408.00	373.00
364.00	372.00	366.00	382.00	360.00	378.00	372.00	349.00	390.00	412.00	387.00
379.00	369.00	388.00	403.00	377.00	368.00	363.00	330.00	367.00	397.00	372.00
343.00	387.00	396.00	402.00	361.00	373.00	359.00	345.00	364.00	331.00	363.00
377.00	340.00	368.00	393.00	393.00	337.00	338.00	365.00	388.00	377.00	380.00
377.00	330.00	345.00	398.00	397.00	388.00	363.00	354.00	368.00	381.00	387.00
377.00	363.00	344.00	342.00	400.00	393.00	380.00	383.00	330.00	364.00	387.00
382.00	380.00	408.00	404.00	386.00	390.00	409.00	361.00	360.00	347.00	415.00
373.00	403.00	380.00	403.00	414.00	396.00	388.00	403.00	412.00	374.00	403.00
334.00	380.00	347.00	407.00	413.00	408.00	396.00	411.00	413.00	405.00	416.00
378.00	336.00	344.00	398.00	406.00	406.00	395.00	415.00	407.00	409.00	421.00
387.00	390.00	393.00	391.00	403.00	409.00	373.00	344.00	390.00	367.00	411.00
348.00	350.00	387.00	390.00	406.00	413.00	410.00	347.00	393.00	413.00	412.00
390.00	405.00	393.00	425.00	414.00	362.00	377.00	390.00	402.00	413.00	412.00
430.00	400.00	396.00	429.00	417.00	374.00	384.00	395.00	356.00	418.00	419.00
418.00	397.00	386.00	432.00	420.00	409.00	364.00	389.00	351.00	398.00	430.00
403.00	411.00	406.00	417.00	422.00	349.00	402.00	390.00	387.00	355.00	427.00
396.00	489.00	406.00	424.00	427.00	371.00	404.00	412.00	400.00	383.00	386.00
391.00	485.00	419.00	428.00	415.00	353.00	374.00	369.00	384.00	388.00	408.00
393.00	368.00	417.00	412.00	395.00	350.00	360.00	373.00	403.00	382.00	400.00
380.00	383.00	369.00	384.00	423.00	359.00	370.00	382.00	379.00	388.00	359.00
377.00	379.00	373.00	421.00	420.00	418.00	373.00	400.00	387.00	402.00	400.00
347.00	370.00	378.00	363.00	418.00	413.00	389.00	419.00	418.00	403.00	401.00
403.00	391.00	365.00	375.00	415.00	416.00	413.00	410.00	408.00	393.00	392.00
414.00	403.00	390.00	343.00	357.00	412.00	409.00	385.00	392.00	378.00	347.00
393.00	390.00	411.00	393.00	356.00	334.00	404.00	383.00	387.00	383.00	418.00
365.00	402.00	411.00	386.00	397.00	405.00	397.00	374.00	372.00	381.00	412.00
370.00	396.00	407.00	388.00	470.00	411.00	390.00	335.00	363.00	383.00	379.00
348.00	359.00	374.00	378.00	352.00	376.00	388.00	382.00	342.00	387.00	383.00
475.00	389.00	482.00	483.00	360.00	371.00	335.00	404.00	403.00	353.00	477.00
381.00	380.00	407.00	407.00	382.00	350.00	403.00	407.00	390.00	340.00	371.00
380.00	371.00	403.00	416.00	400.00	385.00	399.00	422.00	403.00	382.00	428.00
401.00	387.00	382.00	405.00	386.00	403.00	385.00	410.00	409.00	409.00	423.00
400.00	403.00	407.00	348.00	406.00	407.00	409.00	396.00	402.00	408.00	415.00
393.00	398.00	387.00	404.00	390.00	392.00	387.00	391.00	397.00	404.00	349.00
332.00	389.00	407.00	421.00	408.00	380.00	409.00	403.00	388.00	333.00	345.00
388.00	393.00	380.00	407.00	387.00	401.00	400.00	392.00	387.00	330.00	362.00
385.00	391.00	377.00	376.00	394.00	408.00	387.00	382.00	412.00	410.00	378.00
343.00	369.00	372.00	392.00	400.00	392.00	383.00	388.00	424.00	412.00	389.00
405.00	396.00	395.00	385.00	368.00	363.00	371.00	387.00	411.00	414.00	382.00

APPENDIX B: CALIBRATION OF 1/8-IN. PITOT TUBE AND DIFFERENTIAL PRESSURE TRANSDUCER

Instruments

1. Improved accuracy in low-flow velocity measurement was accomplished by using a differential pressure transducer in conjunction with a 1/8-in. pitot tube. The 1/8-in.-OD pitot tube was selected for sensing the stagnation pressure and piezometric pressure in shallow-depth flows. The flow total head and static pressures are transmitted by 1/8-in. plastic tubes from the pitot tube to a variable reluctance differential pressure transducer, Model P90D, Pace Engineering Co. The electrical signal from the transducer feeds into a transducer indicator, Model Pace CD25, which measures the transducer output signal by means of either a digital indicator or a pointer deflection on a meter scale. The manufacturer's stated design operation range for the differential transducer is ± 1 in. of water.

Static Calibration

2. The pressure transducer was calibrated statically by means of the two cylindrical reservoirs containing distilled water (see plate B1). Water elevations in the reservoirs were measured by two hook gages which can be read to 0.001 in. Plate B2 shows the relation between static differential loads applied to the transducer and those registered by the transducer indicator. The calibration was made using reading spans of 500, 600, 800, and 1000. The reading span on the transducer indicator can be adjusted according to the range of the input signal. If the meter reading at span 1000 (or reading at any other span) is known, the meter reading for any desired scale can be found by means of the following equation:

$$M_s = \frac{S \cdot M_{1000}}{1000} \tag{B1}$$

where

S = span

M_s meter reading at span S

M_{1000} meter reading at span 1000

The results of static calibration can be summarized by the equation:

$$M_s = 0.1476 \cdot S \cdot \Delta h \tag{B2}$$

where Δh = differential head, in.

Dynamic Calibration

3. The dynamic calibration consisted of an investigation of the characteristics of the pitot tube and the pressure transducer under dynamic loading. The test was performed in a 14-ft-diam circular rotating tank. Plate B3 shows the linearity of the relation between the velocity head and the meter scale. Comparable static readings for spans 500 and 800 are also shown. The difference between the dynamic and static calibration reflects the pitot tube coefficient which has an average value of 0.98. Plate B4 is a direct plot of tank speed and the corresponding meter readings. Plate B5 is a velocity-meter scale plotted on a full logarithmic coordinate. The following relations were derived from the dynamic calibrations:

$$M_s = 0.1535 \cdot S \cdot h_v \tag{B3}$$

or

$$V = 5.913 \sqrt{M_s/S} \tag{B4}$$

where

h_v = velocity head in inches of water

V = velocity, fps

Discussions

4. General comments are as follows:

a. Angle of attack. According to Sooky,* the pitot tube is insensitive to the attack angle within the range of ±17 deg with respect to the main flow direction.

b. Vibrations. The stem of the pitot tube would vibrate if vortexes were shed periodically from the stem. The vibrations could possibly produce inaccurate results and should not be overlooked, especially under a low Reynolds number flow.

c. Reliability. The reliability or the repeatability of the transducer is reasonably acceptable provided the differential load applied to the transducer is greater than 0.1 in. of water or 0.8 fps in velocity (see plates B3-B5). Overloading the pressure cell 25 percent does not seem to affect the linearity of the transducer output. Further information about the pressure cell can be obtained from the operational instruction technical manual supplied by the pressure transducer manufacturer.

d. Indicator accuracy. It should be emphasized that the accuracy of the indicator as specified by the manufacturer is ±1% full scale reading. This factor accounts for the smaller scattering in the data for the 800 span than for the 500 span in plates B3-B5. Therefore, it is recommended that the largest possible span always be used.

e. Signal detection. The developed instrument should not be used to measure the fluctuation components of the turbulence until an improved pressure transmission system replaces the existing plastic tubing. The latter has a poor frequency response. For measuring the mean velocity of a turbulent flow the digital suppressions control should be used and the meter sensitivity switch set on "IN 10, 30, or 100," depending on the turbulence level. A digital-type voltmeter (integrator) would be desirable for obtaining the mean value of a random signal.

Operation Comments

5. Operation comments are as follows:

a. Air bubble. The equipment should be set level, with the pressure cell located well below the measured flow surface in order to maintain positive pressure on the pressure transducer assembly. After the equipment has been properly connected, it is necessary to remove any air bubbles from

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* A. A. Sooky, "The Flow Through a Meander Flood Plain Geometry," Ph. D. dissertation, Purdue University, 1964.

the fluid transmission lines, pitot tube, and transducer, the following procedures are recommended (refer to plate B1).

(1) Close valves 1 and 3 from the pitot tube and open valve 2. Add sufficient distilled water in either of the containers and then increase the pressure by any means on the container. The air bubbles will be flushed out the bypass tubing and joints.

(2) Immerse the tip of the pitot tube in the test flow and close valves 1 and 3 from the bypass line. Increase the pressure of both water containers separately until no air bubbles can be observed in the tubings.

(3) Close valves 1 and 3 lines from the pitot tube and close valve 2. Loosen bleed screws 1 and 2 separately with a small Allen-head wrench. It will be necessary to move the cell slightly to gain access to the second bleed screw. If the water comes out steadily from the air bleed hole, tighten the screws.

b. Zeroing the indicator. Before turning on the power switch of the indicator, the indicating needle should be adjusted, if necessary, to the zero position. The adjusting screw is directly beneath the end of the needle. Turn the switch on. Open valve 2 until the water levels in both containers are equal. After selecting a proper "Span," switch the sensitivity switch in the "10, SUPPRESSION IN" position. Now adjust the "Zero Dial" until the indicator needle arrives at the zero position and lock it by rotating the concentric ring clockwise. Close valve 2. If the indicator needle deflects from zero, check the level of the equipment.

c. Operation (velocity measurement).

(1) Position the pitot tube against the oncoming flow. Close valves 1 and 3 from the water reservoirs and ensure that valve 2 is closed.

(2) Switch the sensitivity control to the "100, SUPPRESSION OUT" position. Adjust the dial until the pointer returns to zero. Use "SUPPRESSION OUT, 10" for fine adjustment. The digits appearing on the dial would be the meter reading at the particular span.

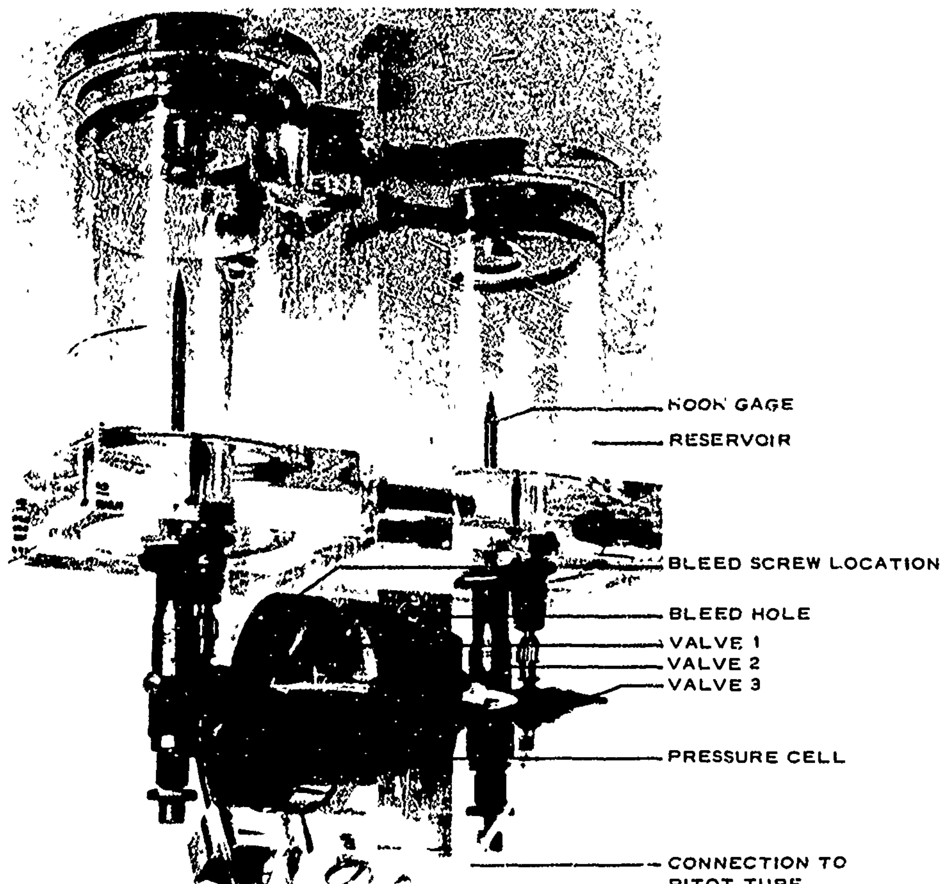
(3) Use plate B4 or equation B4 to find the velocity in feet per second for the obtained meter reading.

(4) After the velocity measurements have been completed, close valves 1 and 3 to the pitot tube and open valve 2. The velocity data should not be considered reliable unless the indicator poirter returns to zero. If the pointer fails to return to zero, it may be that some air bubbles have entered the system during the operation.

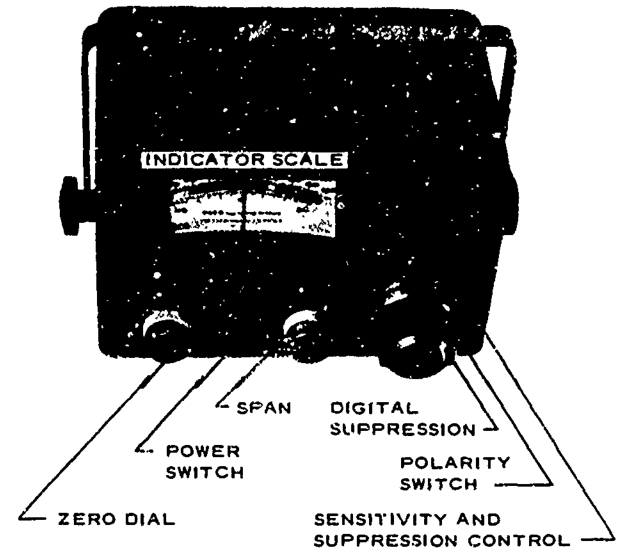
Thus, a careful operation is required for the laboratory personnel.

(5) The water should be drained out from the equipment after a sequence of tests is completed.

(6) Periodic static calibrations are necessary to ensure that the transducer is operating in a normal function.

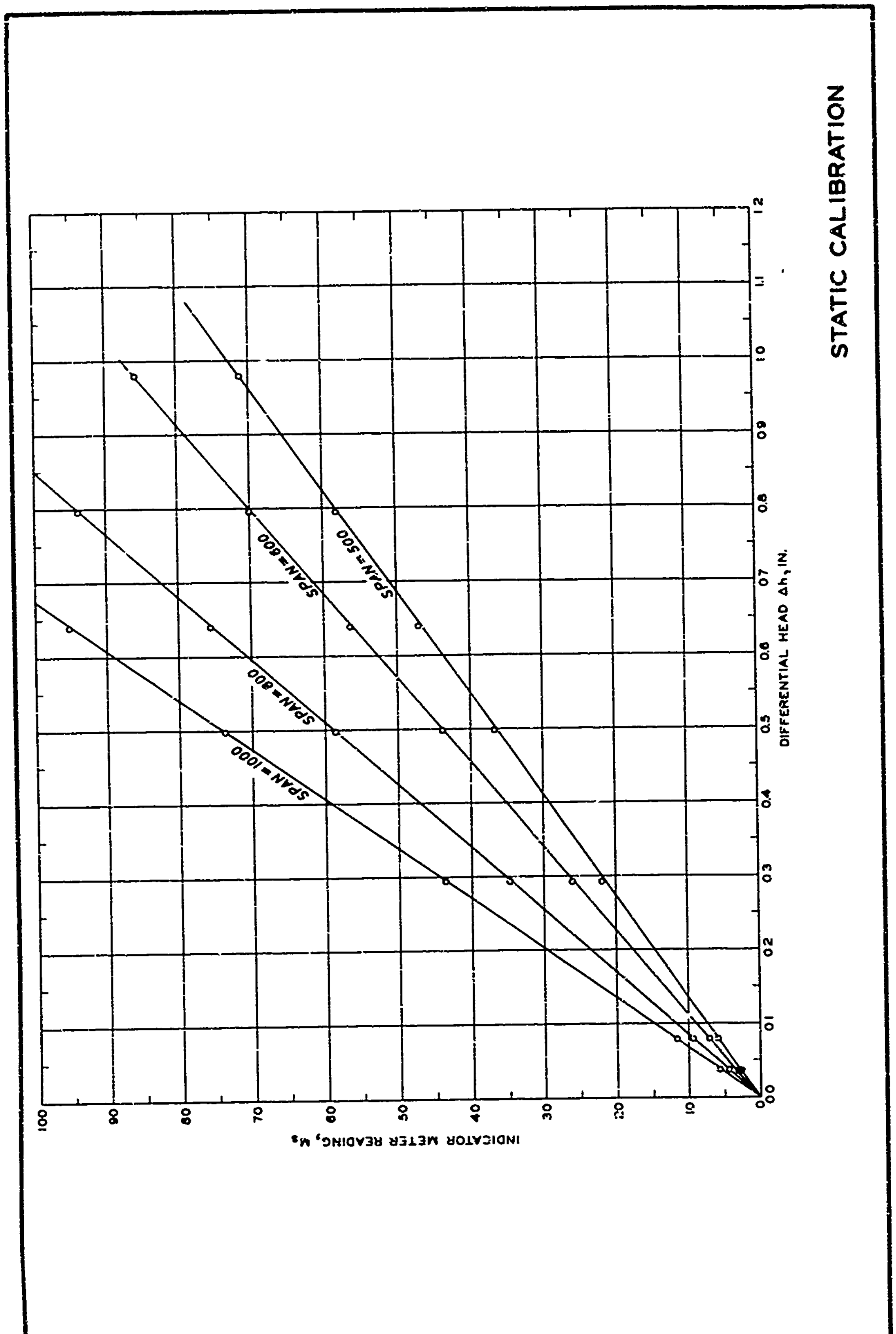


PRESSURE TRANSDUCER AND ACCESSORIES



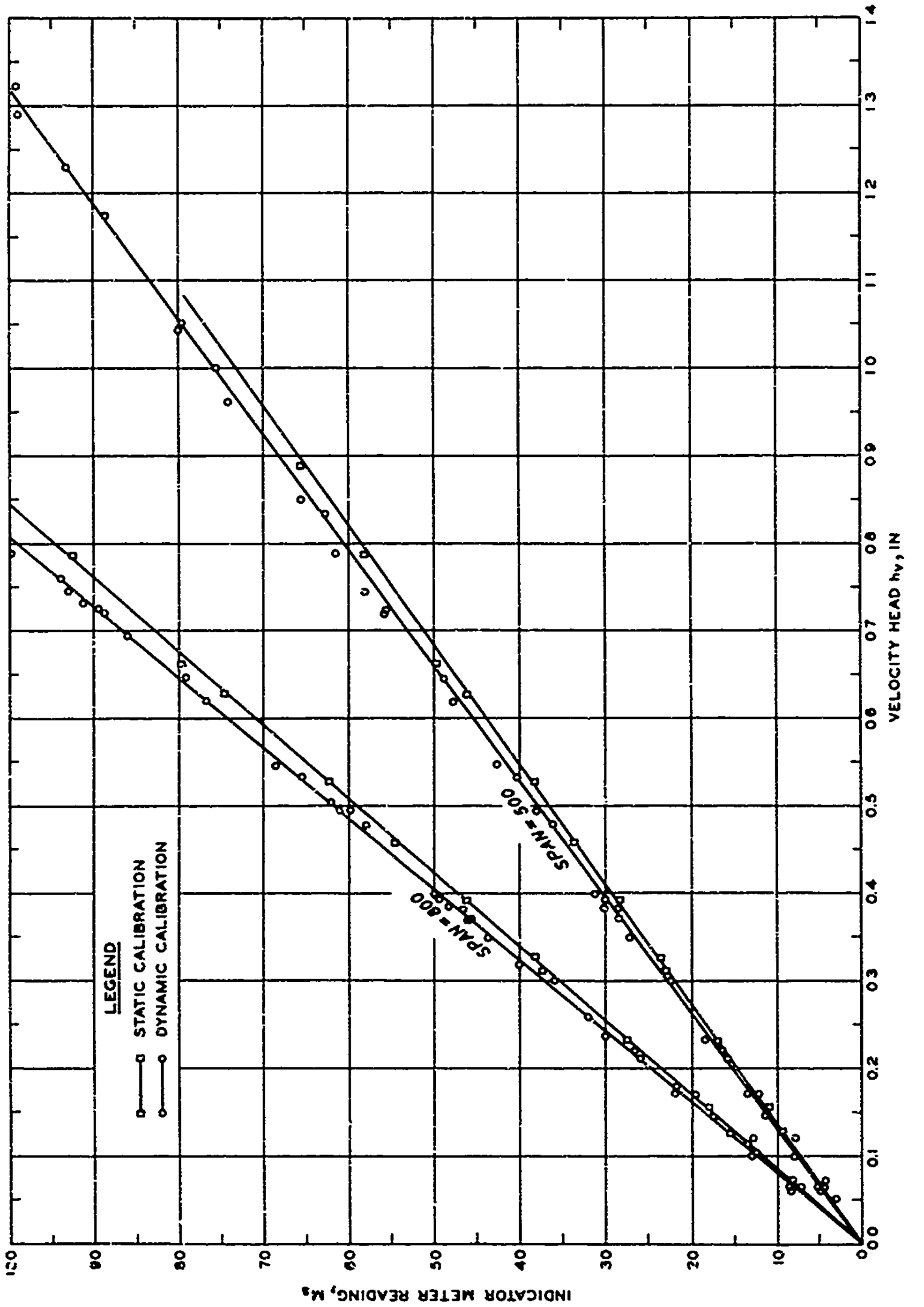
TRANSDUCER INDICATOR

PRESSURE TRANSDUCER
AND ACCESSORIES
AND TRANSDUCER INDICATOR

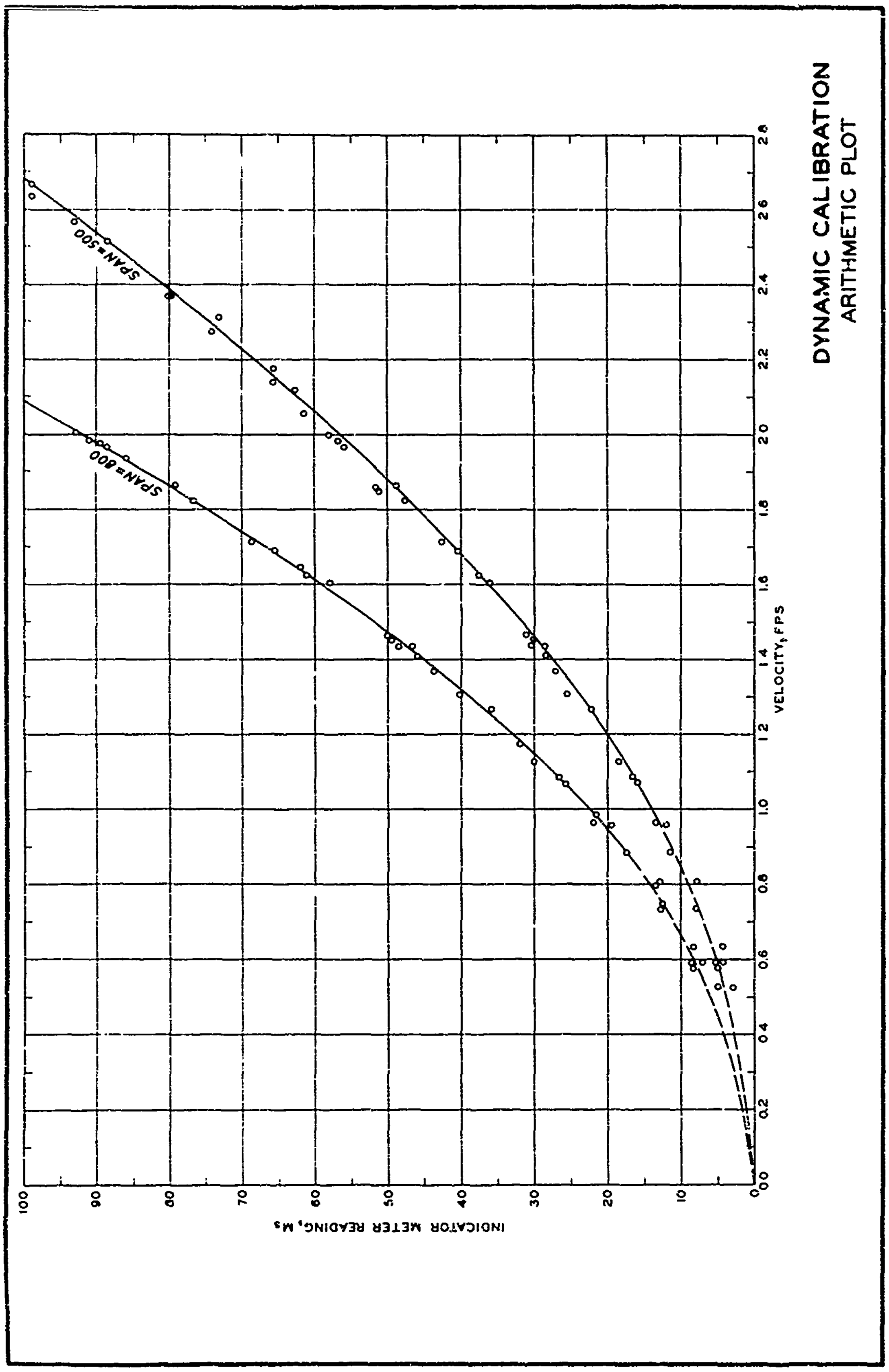


STATIC CALIBRATION
DIFFERENTIAL HEAD Δh, IN.
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
INDICATOR METER READING, Ms
0
10
20
30
40
50
60
70
80
90
100
SPAN = 500
SPAN = 600
SPAN = 800
SPAN = 1000

PLATE B2

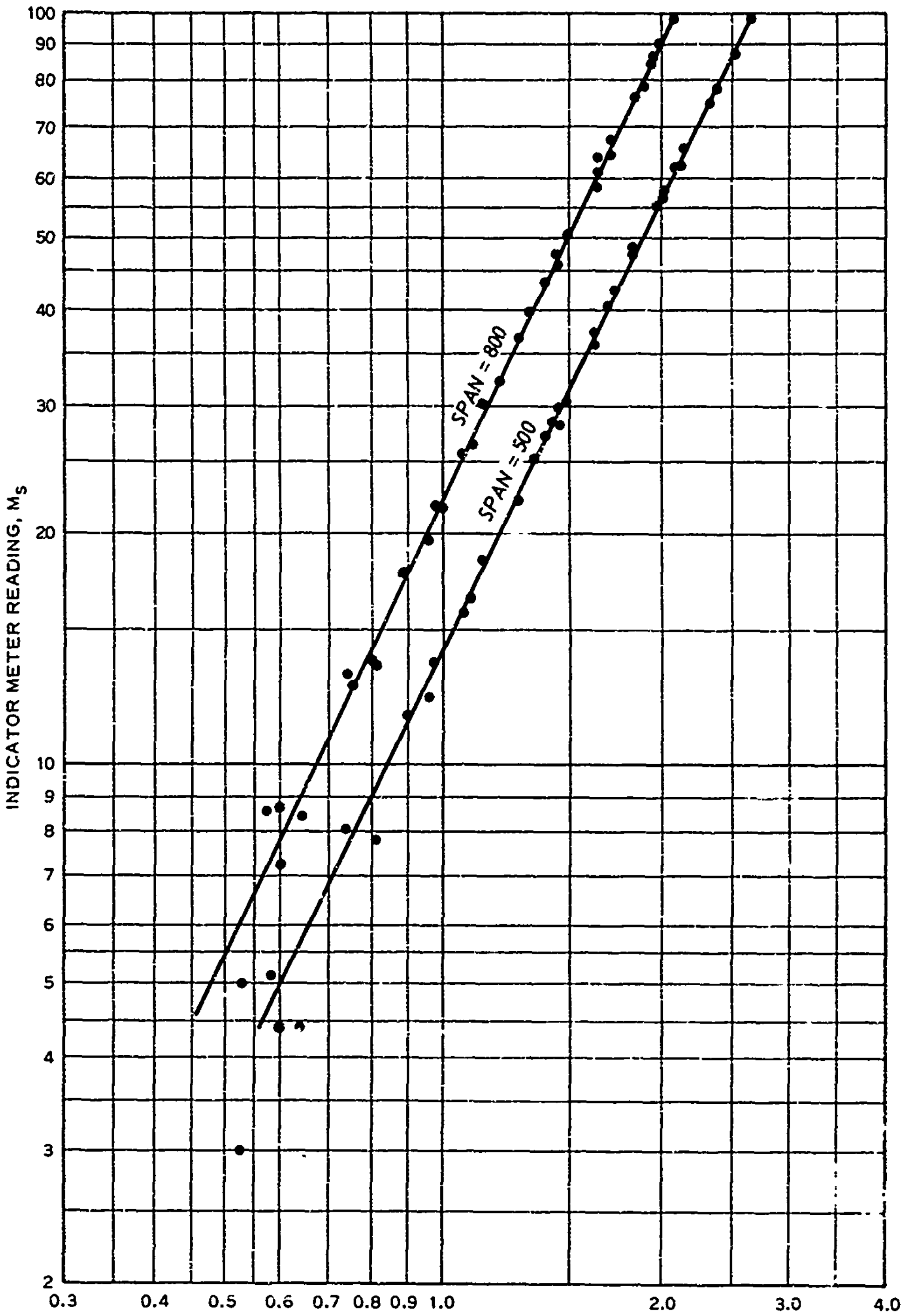


STATIC AND
DYNAMIC CALIBRATION



DYNAMIC CALIBRATION
ARITHMETIC PLOT

PLATE B4



DYNAMIC CALIBRATION

LOG-LOG PLOT

PLATE B5